Risk assessment of the petroleum exploration and production industry from volcanic hazards in the Taranaki region, New Zealand

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ABSTRACT

This thesis considered the impacts of a future Mt. Taranaki eruption to the petroleum sector, with a focus on the gas supply. New Zealand’s petroleum sector is in the Taranaki region, with Mt. Taranaki dominating the landscape. Mt. Taranaki is an active andesitic stratovolcano that is in a quiescence period, with a 50 - 81% chance of eruption within the next 50 years. The research question posed was: what will happen to New Zealand’s petroleum sector and gas supply from a future Mt. Taranaki eruption?

A risk assessment framework was developed for the petroleum sector because of volcanic hazards, including literature review, expert elicitation, and geospatial information systems (GIS). The volcanic risk assessment for the petroleum sector combined a volcanic hazard assessment, an exposure assessment of physical petroleum assets, and a vulnerability assessment of petroleum assets to volcanic hazards. The framework was applied to the Taranaki petroleum sector as a case study. The thesis aimed to produce a holistic risk assessment methodology that can be repeated as data improves, probabilistic hazard modelling is completed, or detailed site-specific studies are realised.

This research has developed a risk assessment framework, including vulnerability models for the four-key asset categories of the petroleum sector to volcanic hazards, wells, pipelines, production facilities and storage tanks. Additionally, critical interdependencies for the petroleum sector have been identified. Findings of this research indicated a large future Mt. Taranaki eruption would likely cause widespread volcanic hazard impacts to the petroleum sector. This has the potential to cause a significant national emergency, due to the loss of the gas supply as a critical lifeline. Enforcement of emergency contingency legislation leaves only 4-6 days of gas supply in the gas network, with no redundancy for the disruption of the extraction sector if all the petroleum sector is disrupted. Major damage to physical assets from volcanic hazards requires lengthy recovery periods, beyond the 5-6 days of available supply. This research assists the New Zealand petroleum sector to understand the hazards and risk from a future Mt. Taranaki eruption, and thus inform risk reduction and readiness actions.

FRONTISPIECE

Taranaki will always have a special place in my heart, despite the short length of this research project, I developed a strong love for this region and volcano (Photo Credit: Zoë Juniper).

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ABBREVIATIONS AND GLOSSARY

APA 6	Publication manual of the American Psychological Association [APA] (6th ed.). The referencing style used for this thesis.
Ashfall	Volcanic ashfall is tephra of < 2mm in diameter (Brown et al., 2015; Deligne & Wilson, 2015).
Block-and-ash flow deposits	The deposits of pyroclastic density currents generated by lava dome collapse (Deligne & Wilson, 2015; Sigurdsson, Houghton, McNutt, Rymer, & Stix, 2015).
Debris avalanche	A rapid and catastrophic mass movement, originating from a landslide that may travel horizontally several times the fall height (Sigurdsson et al., 2015).
Debris flow	A water-saturated mixture of debris that moves downslope under the influence of gravity, in which the solid and liquid fractions are approximately equal volumetrically and in which the two fractions move downstream approximately in unison (Sigurdsson et al., 2015).
Disaster risk	The potential disaster losses, in lives, health status, livelihoods, assets and services, which could occur to a particular community or society over some specified future period (UNISDR, 2009).
Disaster risk management	The systematic process of using administrative directives, organisations, and operational skills and capacities to implement strategies, policies and improved coping capacities to lessen the adverse impacts of hazards and the possibility of disaster (UNISDR, 2009).
Fragility functions	A quantitative based model that provides a robust relationship between volcanic impact and hazard intensity using mathematical equations (G. Wilson, Wilson, Deligne, Blake, & Cole, 2017).
Hazard intensity metrics (HIMs)	A descriptive of the intensity of a volcanic hazard at a location using a range of properties that convey the intensity but is independent of vulnerability or fragility functions. For example, the temperature range in ˚C (G. Wilson et al., 2017).
Mt. Taranaki	The topographic name for the latest cone within the Egmont Volcanic Centre, also known as Egmont Volcano or Taranaki Volcano in the scientific literature (Alloway, Neall, & Vucetich, 1995).
Lahar	An Indonesian term most commonly defined as a rapidly flowing, gravity-driven mixture of rock, debris, and water from a volcano.

	A lahar can vary in character with time and distance downstream (Sigurdsson et al., 2015).
Lifelines	Lifeline infrastructure includes the transport, energy, communications and water services sectors that are fundamental to communities and economy (New Zealand Lifelines Council, 2017).
PEPANZ	Petroleum Exploration & Production Association of New Zealand. The upstream petroleum sectors political lobby group.
Petroleum sector	Refers to the upstream petroleum sector for this document, comprising the assets, staff, processes and governance involved in the exploration, extraction and processing of raw petroleum or hydrocarbons.
Petroleum Sector - down-stream	Refining and distribution of petroleum products. For example, Liquid Petroleum Gas (LGP) is used to produce propane, butane and isobutane. Oil is refined into products such as transport fuels, naphtha or bitumen (Schlumberger, n.d). LNG products (liquified methane/ethane (natural gas)) is not produced in NZ.
Petroleum Sector – mid-stream	Transmission and storage of petroleum products (Schlumberger, n.d).
Petroleum Sector – up-stream	Petroleum exploration, extraction & onsite processing/treatment and separation of raw petroleum types of oil, gas and condensate (Schlumberger, n.d).
Pyroclastic density current (PDC)	Hot eruption-derived particulate-gas density current that moves laterally along the ground. This term encompasses pyroclastic flows and pyroclastic surges (Sigurdsson et al., 2015).
Tephra	Tephra is a term used for volcanic material created via magma fragmentation (Brown et al., 2015).
Volcanic alert level (VAL)	The New Zealand Volcanic alert system that has levels 0-5 to notify the public of the scientific activity of volcanoes (Potter, Jolly, Neall, Johnston, & Scott, 2014).
Volcanic explosivity index (VEI)	An eight-point scale used to estimate the explosive magnitude for volcanic eruptions globally based on the volume of erupted material, the height of the eruption plume and the duration of the eruption (Newhall & Self, 1982).
Volcanic hazard	A potential threat to humans and their welfare arising from a volcano that may cause loss of life, injury, property damage, and other community losses or damage (UNISDR, 2009).
Volcanic impact	The damage or disruption caused by volcanic hazards (G. Wilson et al., 2017).

Vulnerability — The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard (UNISDR, 2009).

Vulnerability matrices — A quantitative based model that provides a robust relationship between volcanic impact and hazard intensity, using a matrix to represent the theoretical response of the physical assets to volcanic hazards to capture damage thresholds (G. Wilson et al., 2017).

1.0 INTRODUCTION

1.1 Context of the Study

Volcanoes represent one of the most damaging although less frequent natural hazards that impact human societies and associated critical lifeline infrastructures (Loughlin, Sparks, Brown, Vye-Brown, & Jenkins, 2015). Globally and historically, a wide range of volcano types, sizes and associated volcanic hazards have impacted human societies (Loughlin et al., 2015). Population number and footprint increases of human habitation have increased the number of societies that now live in areas vulnerable to volcanic hazards. As these societies have developed, the lifelines services and infrastructure have increased in technological complexity, often without resilience to the infrequent volcanic hazards (G. Wilson, Wilson, Deligne, & Cole, 2014). Volcanic hazard impacts on critical lifeline services are affected by the size, style and duration of the volcanic eruption along with the topography of the area. Additionally, the exposed assets and dependent populations influence the vulnerability of the critical lifeline services. Volcanic risk assessments combine these three elements in a structured approach to understand the potential impacts of future eruptions and inform risk reduction and readiness actions for the impacted lifeline services and populations (G. Wilson et al., 2014).

In New Zealand, many lifelines are exposed to volcanic hazards, with the Taranaki region being a key area for national lifelines. The Taranaki Volcanic Succession comprises of four volcanoes; the youngest is Egmont Volcano/ Mt. Taranaki (Alloway et al., 1995; Neall, Stewart, & Smith, 1986). Mt. Taranaki has shaped the Taranaki landscape over the last ~130,000 years, through at least 228 eruptions, the last only 150 years ago (Damaschke, Cronin, Holt, Bebbington, & Hogg, 2017). Mt. Taranaki is an active 2518 m high andesitic stratovolcano that is in a quiescence period, with up to an 81% chance of eruption within the next 50 years (Green, Bebbington, Cronin, & Jones, 2013). Despite this, perceptions of volcanic risk are very low among many Taranaki locals (Finnis, Johnston, & Paton, 2004). Mt. Taranaki has produced a range of eruption sizes, styles and volcanic hazards throughout its history, from small effusive eruptions to large explosive eruptions (Neall et al., 1986). Volcanic hazards range from fine ash through to large debris avalanches, with these hazards reaching distances many 10's km away and ash distributed over 100's km (Loughlin et al., 2015). Additionally, Taranaki region has been impacted by distal ash deposits from nearby Tongariro Volcanic Centre, 140 km to the east. New Zealand's upstream petroleum sector is strategically placed around the Taranaki region, comprising both on-shore and off-shore extraction and production facilities and a network of petroleum pipelines (Hull, 1996). All New Zealand's critical lifeline gas service is extracted from the Taranaki region (New Zealand Government, 2017). The gas provides an energy source for electricity generation stations, large industrial users, businesses and domestic gas supplies (New Zealand Government, 2017).

There are large gaps in knowledge about how volcanic hazards impact petroleum sector infrastructure (Hull, 1996; Johnston et al., 2011). A literature review of published work identified only one documented volcanic eruption having impacted a petroleum fuel storage terminal and pipeline (Redoubt Volcano, Alaska, 1990 and 2009) (Bull & Buurman, 2013; Dorava & Meyer, 1994). The active nature of Mt. Taranaki means New Zealand's petroleum sector is likely to be impacted by a future eruption. Therefore, understanding what the likely volcanic hazards are and impacts is a priority for New Zealand's critical lifeline sector, which can be achieved through raising awareness and undertaking a volcanic risk assessment. This research aims to assist the New Zealand upstream petroleum sector to understand the hazards and risks from a future Mt. Taranaki eruption, and thus inform potential risk reduction and readiness actions.

1.2 THESIS OBJECTIVES

The overall goal of this work is to develop a risk assessment framework for the petroleum sector for volcanic hazards, using the Taranaki region in New Zealand as a case study. The objectives of this thesis are to:

1. Develop a methodology for volcanic risk assessment framework of the upstream petroleum sector.

   The initial objective uses standard risk assessment approaches to develop a volcanic risk assessment framework for the petroleum sector through the following methodological steps:

   a) **Hazard assessment (Chapter 2).** Past eruptions and analogues of similar volcano types indicate the likely hazards and their geographical extent. Analysis of the locations of sector assets may determine if some hazards are irrelevant to the study based on distance. Maps are compiled or constructed for the area and hazards in consideration, and hazard scenarios developed to use for the risk assessment.

   b) **Exposure assessment (Chapter 3).** For the petroleum sector, methodologies used to complete the exposure assessment include a literature review, expert elicitation and sector engagement, to understand the assets and petroleum system. The development of a system map helps identify the level of study, in this case, a holistic approach. The identification and assignment of categories of the physical assets, based on their functionality completes this step.

   c) **Vulnerability assessment (Chapter 4).** Vulnerability models combine the identified hazards and asset categories to identify the hazard intensity metrics and thresholds for each asset type. The development of the models uses a combination of literature research and expert elicitation. For the Taranaki case study, a theoretical approach is taken, due to the lack of previous exposure of the petroleum sector to volcanic hazards.

   d) **Risk assessment (Chapter 5).** Risk assessment development combines the hazard, exposure and vulnerability assessments for the petroleum sector. The developed vulnerability models are used to assign damage impact values to the various asset categories and overlapped with the hazard scenarios to provide a deterministic risk assessment. Additionally, the operational systems and subsystems of the petroleum sector are mapped out using expert elicitation and literature review, to produce a fault map and identify dependencies on other lifelines.

2. Apply the framework to Taranaki as a case study.

   The second objective utilises volcanic eruption hazard scenarios for the Mt. Taranaki to undertake a physical asset risk assessment of the upstream petroleum sector in the Taranaki region. At each step of the risk assessment framework the scope of the project is documented and justified for the Taranaki case study, noting where exclusions, inclusions or limitations are imposed or encountered.

3. Develop volcanic risk recommendations for building resiliency in the upstream petroleum sector through the risk assessment process.

   The third objective considers recommendations for improving resilience, drawn from the case study, for the use of the scientific communities and policymakers to recognise key focus areas for future work. The experiential process of this thesis provides scientific knowledge of volcanic hazards to the petroleum sector. Additionally, the science community and Taranaki civil defence gain insight into the operational workings and challenges of the petroleum sector.

1.3 DISASTER RISK MANAGEMENT (DRM)

Disaster Risk Management (DRM) is: "The systematic process of using administrative directives, organisations, and operational skills and capacities to implement strategies, policies and improved coping capacities to lessen the adverse impacts of hazards and the possibility of disaster" (UNISDR, 2009, p.10).

The 4R's approach is acknowledged globally in the field of emergency management and disaster risk reduction when considering how disasters and disruptions impact society (Rovins et al., 2015). The 4R's approach (Reduction, Readiness, Response and Recovery) is used to plan and prepare for, respond to, and recover from disruption or disasters from natural and human-made events (Coppola, 2011). Identification and risk assessments of hazards underpin any actions or decision-making which impacted communities or organisations will make in the 4R's approach (Rovins et al., 2015). Volcanic risk assessment can be used to assist the petroleum sector in identifying and quantifying risks. The petroleum sector uses such information to improve their resilience to future Mt. Taranaki eruptions by developing and prioritising reduction and readiness actions and developing response and recovery planning for critical petroleum infrastructure.

1.3.1 DRM in a global context

In 2015 the United Nations General Assembly endorsed The Sendai Framework for Disaster Risk Reduction 2015-2030, setting out seven global targets and four priorities for action for pledged governments (Aitsi-Selmi, Egawa, Sasaki, Wannous, & Murray, 2015; Wahlström, 2015). Priority 1 aims to improve understanding disaster risk and states:

> Disaster risk management should be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment. Such knowledge can be used for risk assessment, prevention, mitigation, preparedness and response (UNISDR, 2015, p. 14).

New Zealand has joined over ninety other UN member states adopting the Sendai Framework and is working towards goals that include developing a new National Disaster Resilience Strategy (Wahlström, 2015). A key aspect of this strategy is understanding disaster risk and how it impacts society, by considering six critical areas of society that disasters impact. Of interest to this study is the “Resilience of the Built Environment” concept area, which includes the provision of essential services, such as energy (Figure 1.1) (MCDEM, 2016).

Figure 1.1 Concept of National Resilience (MCDEM, 2016, p. 7).

Human-made systems and networks built to facilitate the distribution of goods, services and information that human populations rely on for everyday lives are known as critical lifeline services or lifelines infrastructure (Giovinazzi et al., 2016; Platt, 1991). Lifeline services vary between countries (MCDEM, 2017). Examples of lifelines include:

- water
- energy
- transport
- health
- food
- financial services
- communications
- governance.

The objective of every country is to improve the resilience of their critical infrastructure to disasters to reduce the impact on these essential services when disasters occur (Coppola, 2011; O'Rourke, 2007). The ability to measure resilience remains elusive due to the complex nature of predicting a reaction by multiple dynamic components to a future event (Norris, Stevens, Pfefferbaum, Wyche, & Pfefferbaum, 2008). However, drawing on links between four key characteristics of risk and resilience, Mitchell and Harris (2012) concluded that systems that can manage risk effectively are more likely to be resilient. Many critical infrastructure service providers are represented as a system of connected components, each with vulnerabilities and exposure thresholds. Risk assessment processes are then used as a proxy for measuring resilience.

Major disasters in recent decades have tested lifeline infrastructure across the globe, leading to extensive research around lifeline vulnerabilities and the importance of lifelines in DRM (UNISDR, 2017). Hazard risk assessment studies consider a range of impacts to lifelines from direct physical impacts, indirect impacts, interdependencies between lifelines, or economic loss. Interdependencies between lifeline services are recognised as a challenge, as many lifeline services share network locations, with systems reliant on and influencing each other

(O'Rourke, 2007; Reed, Kapur, & Christie, 2009). For example, water pumps and telecommunications both require electricity to work. DRM needs to consider complex industries such as the oil and gas sector when undertaking risk assessments and planning resilient critical lifeline infrastructures for communities.

1.3.2 DRM in a New Zealand context

New Zealand's DRM framework consists of the Civil Defence and Emergency Management (CDEM) Act 2002, supported by a CDEM Strategy, Plan, and Guideline documentation based on the 4R's (MCDEM, n.d.). New Zealand is divided into 16 regional groups that follow local and regional council boundaries; each group is responsible for identifying and understanding hazards and risks for their region and preparing a plan to manage the hazards and risks based on the 4R's (MCDEM, n.d.). Lifelines form a key part of both the regional plans and the national plans, where lifelines such as electricity and gas are national networks, while water networks are regionally managed resources. The overarching Civil Defence and Emergency Management Act states: "Every lifeline utility must ensure that it can function to the fullest possible extent, even though this may be at a reduced level, during and after an emergency" (Civil Defence Emergency Management Act 2002, 2017, Section 60).

Provisional high-level work has already been undertaken in this area in New Zealand to assess the vulnerability of the country's lifelines (New Zealand Lifelines Council, 2017). This study compiles the regional plans into a single national level plan. Currently, the New Zealand national lifeline services recognise four high-level critical infrastructure areas: water, transport, energy and telecommunications (MCDEM, 2017; New Zealand Lifelines Council, 2017). These areas can be broken down into sub-sectors:

- water
  - water supply (extraction and distribution)
  - wastewater (distribution, processing and disposal)
  - stormwater (distribution, processing and disposal)
- energy
  - fuel (road, marine and aviation fuels)
  - electricity (generation, transmission and distribution)
  - gas (extraction, transmission and distribution)
- transport
  - road
  - rail
  - maritime (including harbours)
  - aviation
- telecommunications
  - radio
  - television
  - mobile and landline telephone networks
  - internet providers

New Zealand lifeline groups have traditionally focused on seismic resilience with both the Wellington and Alpine fault anticipated to rupture (Wellington Lifelines Group, 2012). Further research focused on seismic risk following the Christchurch Earthquakes (2010 and 2011) and Kaikoura Earthquake (2016) (Gerstenberger, McVerry, Rhoades, & Stirling, 2014; Kongar, Giovinazzi, & Rossetto, 2016; Robinson & Rosser, 2017; Taylor, Chang, Elwood, Seville, & Brunsdon, 2012). Volcanic and tsunami hazards are now additional areas of focus, with the Auckland Volcanic Field and the East Coast Tsunami risk in the spotlight. Gaps in knowledge exist of complex industrial sectors such as Petroleum, which are run by corporate organisations or private companies, and who are challenging to engage with (New Zealand Lifelines Council, 2017). Additional gaps for New Zealand's lifelines include regional volcanic assessments outside Auckland, volcanic hazard modelling, impacts of volcanic hazards, lifeline interdependencies, and cascading hazards (New Zealand Lifelines Council, 2017).

1.3.3 Volcanic hazards and volcanic risk assessment in DRM

Volcanic risk, while being less likely than other hazards, has large consequences, with even small eruptions such as Agung Volcano (2017) and Eyjafjallajökull Volcano (2010) causing widespread disruption. Globally over 600 million people and the associated infrastructure that support those communities have the potential to be impacted by volcanic hazards (Sparks, Aspinall, Crosweller, & Hincks, 2012). In many instances, volcanoes have a limited but valuable warning period as unrest develops into an eruption (Coppola, 2011). Technology has advanced to improve monitoring and warning systems, especially for volcanoes close to human habitation (Sparks, 2003). However, even with warning systems, communities that live in the shadow of volcanoes face long-term disruption and economic losses. Eruptions have resulted in disruption, damage and destruction to services, buildings and infrastructure, as well as loss of life (Jenkins, Spence, Fonseca, Solidum, & Wilson, 2014; G. Wilson et al., 2014; T. M. Wilson et al., 2012).

Volcanoes produce a wide range of hazards that vary between volcanoes and eruptions (Figure 1.2), causing difficulty in predicting future volcanic hazards from individual volcanoes. Volcanic hazards are the geological processes produced during an eruption that has the potential to disrupt, damage or kill humans. Not all volcanic hazards are produced in every eruption and vary according to eruption size and style, linked to the geochemistry (Sigurdsson et al., 2015). Some volcanic hazards are limited spatially, such as andesitic lavas, while ash can travel many hundreds of kilometres and cause widespread disruption to society (Sigurdsson et al., 2015). For example, in April and May 2010 Eyjafjallajökull eruption, Iceland, shut down the European airspaces and disrupted global travellers for some weeks, causing sizeable economic losses to business globally (Lund & Benediktsson, 2011).

Volcano eruptions are measured using an eight-level scale that includes a volcanic explosive index (VEI) that communicates the size of volcanic eruption based on the plume height and volumes of tephra produced (Newhall & Self, 1982). The larger the eruption size and footprint, generally the higher the risk of impacts, however, smaller eruptions occur with higher frequency and are equally capable of substantial disruption and fatalities (Loughlin et al., 2015). Associated with the size is a description of the eruption type or classification from Hawaiian through to Ultra-Plinian, and the magmas geochemical type (Sigurdsson et al., 2015).

For countries with volcanoes, understanding the distribution of volcanoes, their potential eruption type, style, and size in regions where the volcanic hazards can have direct or indirect impacts on human lives is a priority (Loughlin et al., 2015). Risk assessments of volcanic hazards help those countries to reduce risk reduction and increase the readiness of their communities ahead of future eruptions (Jenkins, Spence, et al., 2014).

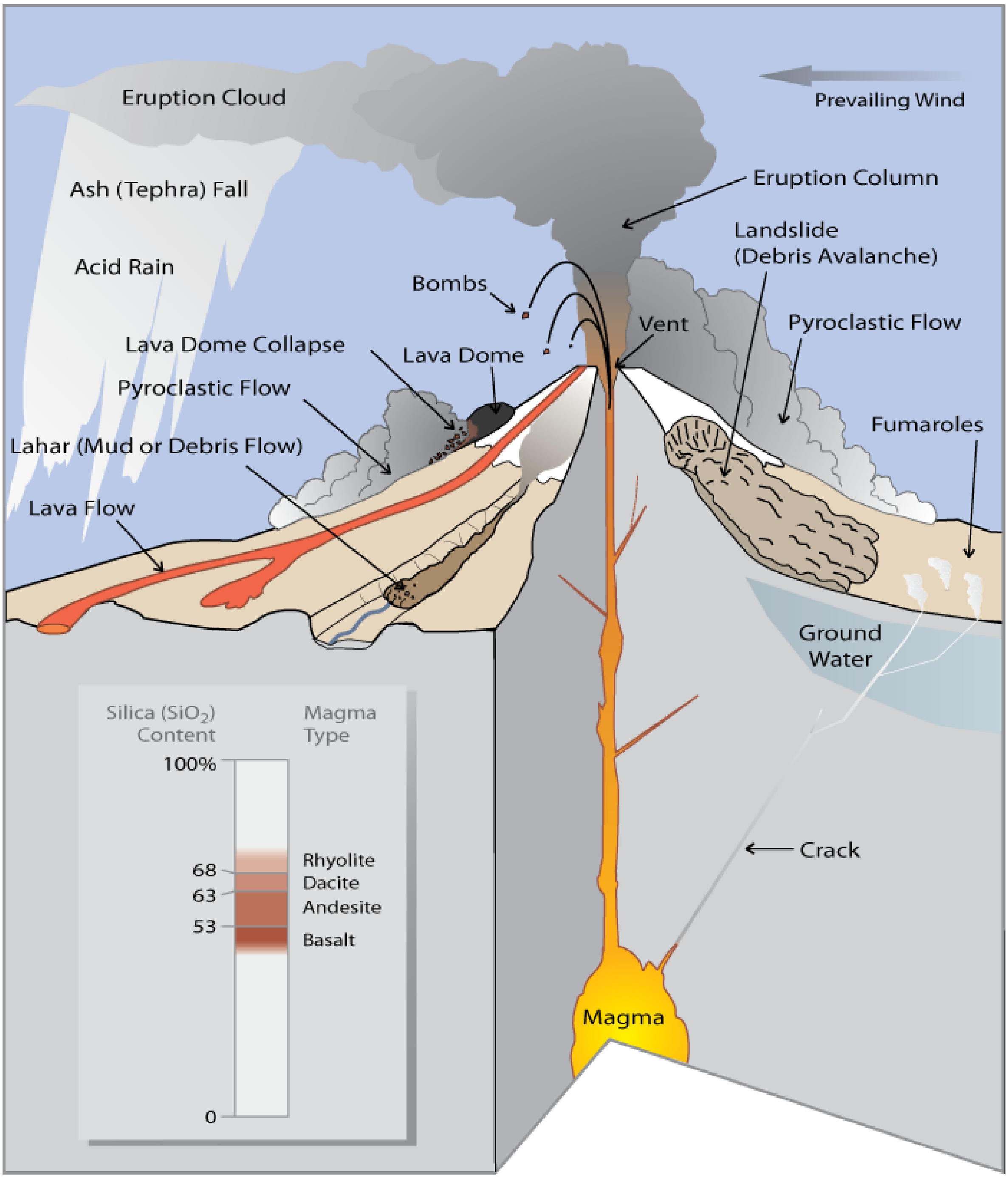

Figure 1.2 Potential volcanic hazards (U.S.G.S., n.d.).

1.4 Petroleum Sector

Energy is an essential part of modern society, encompassing transport fuels, electricity and gas. Fossil fuels (petroleum and coal) are fundamental for modern energy needs, contributing to electricity generation (coal and gas), road fuels (oil) and gas (piped or bottled). The use of petroleum as an energy source rose rapidly in the 1850's and has since grown into a readily available global commodity, replacing limited access and use of alternatives such as whale or penguin oil. The world currently consumes approximately 4.3 Mt (metric ton) of oil per day and 3.6 bcm (billion cubic metres) of gas, presenting over 50% of the world energy supply source (International Energy Agency, 2017a). Most nations formally recognise the need to move away from burning high carbon-emitting fuels such as coal and oil to pursue near-zero-emission energy systems, reduce pollution, and slow anthropogenic-driven climate change. However, petroleum is woven into the fabric of society and global economies, and will likely remain a lifeline service in the global energy mix on the medium to long-term, notably with transition fuels such as gas (International Energy Agency, 2017b).

The petroleum sector encompasses exploration for oil and gas resources, extraction, processing, distribution and finally retail sales of final products, divided into three sub-sectors (Figure 1.3). Petroleum resources are extracted from "fields" or reservoirs buried 3-4 km below the surface that take many millions of years to develop (Allen & Allen, 2013). Accumulations of organic material are buried in anaerobic environments and maturate at great depths and high temperatures in sedimentary basins, eventually expelling oil, gas and condensate into surrounding porous rocks (Allen & Allen, 2013). These accumulations are then trapped by sedimentary structures or non-permeable rocks in reservoirs or fields until discovered and extracted by oil companies.

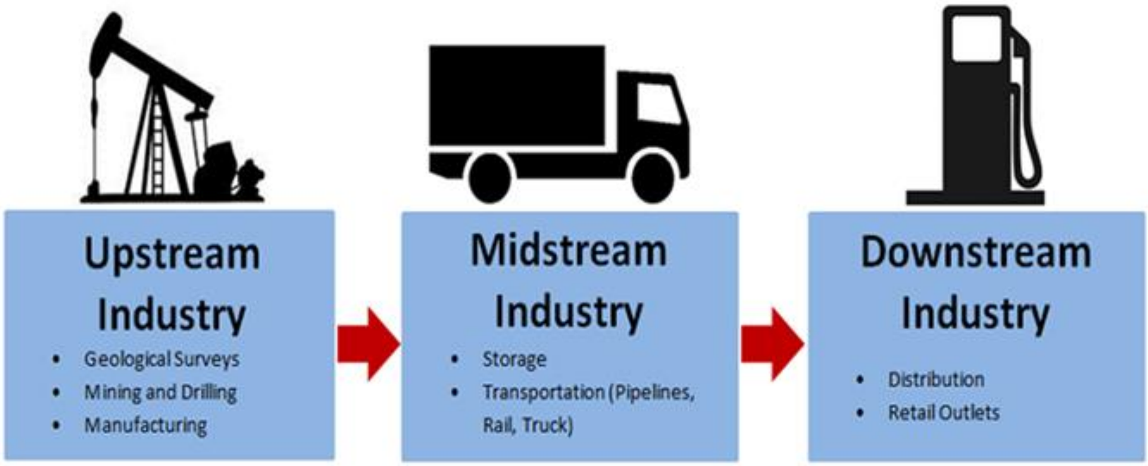

Figure 1.3 The three sectors that make up the Petroleum industry (Energy Education, n.d.).

Rapid development and exploration of petroleum were initially undertaken with less concern for health and safety and natural hazard risk. However, the petroleum sector has since developed comprehensive risk management systems for their operations, especially after industrial disasters such as Deepwater Horizon (2010), Gulf War (1991), and Piper Alpha (1988) and exposure to natural hazards such as Hurricane Katrina (2004) that disrupted the sector and caused damage (American Society of Civil & Wind-Induced Forces Task, 2011; Bratspies, 2011; Brinkley, 2007; Hull, 1996; Reader & O'Connor, 2014; Skogdalen & Vinnem, 2012). These disasters also brought about closer public scrutiny and expectations of higher standards, enforced through legislation and regulatory oversight (Bratspies, 2011). As exposure to natural hazards causes increasing impacts on the industrial sectors such as petroleum, review the less frequent hazards, such as volcanic eruptions to understand the importance of risk (Krausmann, Cozzani, Salzano, & Renni, 2011). However, only one example of volcanic hazards impacting the petroleum sector was found during the literature review, Drift River Terminal, Alaska (see Section 4.2.3), highlighting the infrequency of volcanic hazard impacts on this sector. Volcanoes and modern petroleum extraction industries rarely coexist, with volcanism following the tectonic plate boundaries and petroleum resources generated in mature sedimentary basins away from active deformation zones (Figure 1.4).

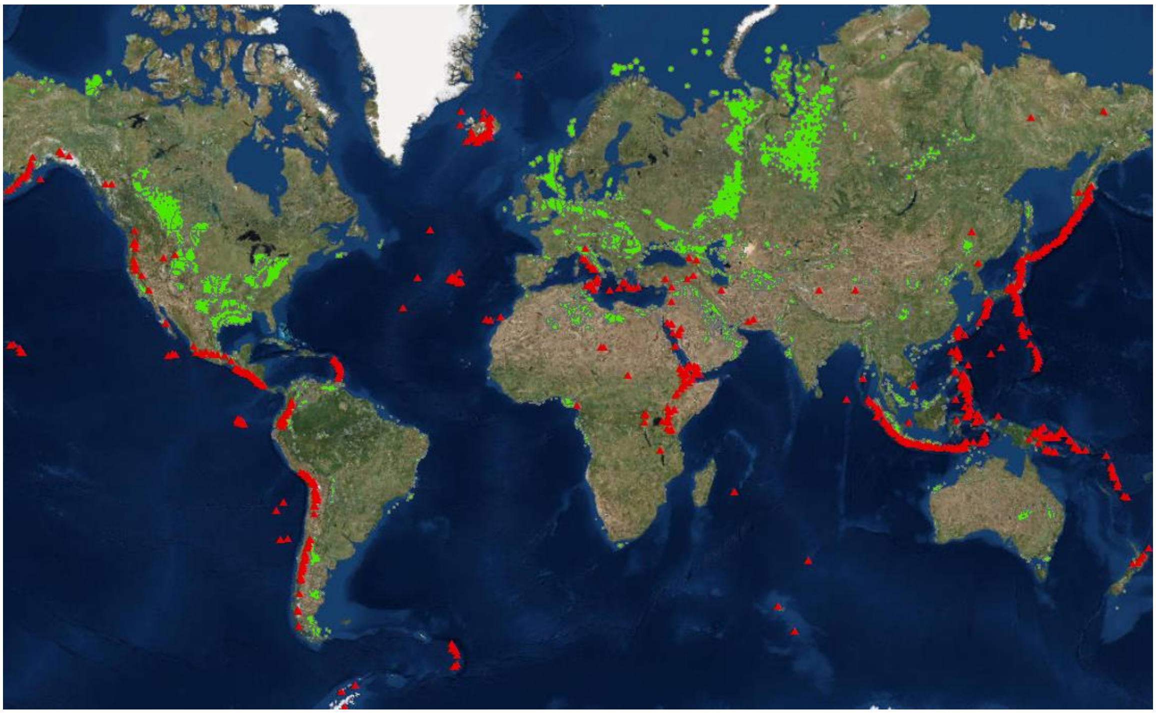

Figure 1.4 Map of active Volcanoes (red) (Kerski, 2011), and known petroleum fields (green) (Lujala, Rod, & Thieme, 2007).

1.4.1 The New Zealand petroleum sector

The Taranaki region of New Zealand is the only petroleum-producing basin in New Zealand, supplying all New Zealand's gas supply. The Petroleum sector contributes $2.5 billion annually to New Zealand's Gross Domestic Product, making it the largest maritime revenue generating sector for New Zealand (Petroleum Exploration and Production Association of New Zealand, 2017). While New Zealand has an active petroleum upstream sector located in the Taranaki region, it is tiny on a global scale, producing just 0.12% of the world's energy production (International Energy Agency, 2017a). New Zealand produces 78% of its own energy needs, a total of 718 PJ (Petajoules) of Energy, with oil and gas accounting for 178 PJ (New Zealand Government, 2017). New Zealand produces 82 PJ of oil, with an additional 355 PJ of light crude imported to meet the demands from transport fuels (New Zealand Government, 2017). Most of the oil and condensate extracted in New Zealand is exported overseas as the local refinery Marsden Point is unable to process the heavier oils from Taranaki's reservoirs.

New Zealand produces enough gas to meet all of its domestic demand, with 100% of gas extracted in the Taranaki region; 84% from just four fields (Figure 1.5) (New Zealand Government, 2017). The extracted gas is used:

- to produce electricity, for example by Stratford or Huntly Power stations
- by large industrial users such as Methanex to produce methanol
- by the dairy industry to process the milk
- by commercial users such as the hospitality and medical sector
- by residential users for heating and cooking.

The "dry" gas is distributed around the North Island by the First Gas transmission pipeline into local distribution networks owned by third parties. The petroleum sector uses the gas to generate Liquid Petroleum Gas (LPG) products (liquefied propane and butane, which is then transported to the South Island or exported and used for bottling for BBQ's or domestic bottled gas supplies for cooking or heating, or process fuels for industrial users. At present New

Zealand cannot import “dry” gas from abroad, only LPG, and is too remote for cross-border gas pipelines like in Europe. The New Zealand gas market is isolated from the rest of the world, which combined with the single geographical region for all gas extraction makes it a vulnerable lifeline sector.

New Zealand’s first petroleum discovery was in 1865 on New Plymouth Beach, with modern commercial production following the onshore Kapuni gas-condensate discovery in 1959, just 22 km from Mt. Taranaki vent. Following this a large offshore petroleum discovery was made in 1969. The Maui production commenced in 1979 making New Zealand self-sufficient in gas resources (Petroleum Exploration and Production Association of New Zealand, 2017). New Zealand currently has 25 producing oil and gas permits/licences around the onshore and offshore Taranaki Region, where all onshore facilities are within approximately 55 km of Mt. Taranaki (Figure 1.5). There are a total of nine gas production companies in New Zealand, processing petroleum at thirteen production facilities (Table 1.1) from twenty different gas producing fields or reservoirs all located in the Taranaki Region (Critical Contingency Operator, 2017; New Zealand Government, 2016). Much of New Zealand’s oil production is transported by pipeline or road around the Taranaki region and stored in the New Plymouth Tank farms before being exported to overseas refineries.

Table 1.1 List of New Zealand gas producers (New Zealand Government, 2016).

Field	**Operator**	**2016 Net Production %**
Pohokura	Shell Exploration NZ	37.0
Maui	Shell Taranaki Ltd.	19.2
Mangahewa/McKee	Todd Energy	14.2
Kupe	Origin Energy	13.0
Ngatoro/Kowhai/Turangi	Greymouth Gas NZ	9.8
Kapuni	Vector Gas Trading/Todd Energy	5.9
Rimu/Kauri	Westside New Zealand	0.4
Cheal/Sidewinder	TAG Oil (NZ)	0.4

A systems approach is necessary to understand the petroleum production industry in New Zealand. The sector is a complex one both in the organisational space and systems processes. Figure 1.6 takes a snapshot view of the organisations involved in the industry from the regulatory oversight agencies to the many companies involved in exploration, production, distribution, storage, processing and some of the contracted companies. Regulatory agencies operationalise legislations that govern the petroleum sector, shown in Figure 1.7. The primary legislation, regulations and standards cover various aspects of the industry; these are summarised in Appendix A (7.0A3.0) and include:

- minerals rights,
- construction and design standards,
- health and safety,
- business continuity,
- emergency management,
- environmental impacts on air, water, ground,
- industrial operations,
- products.

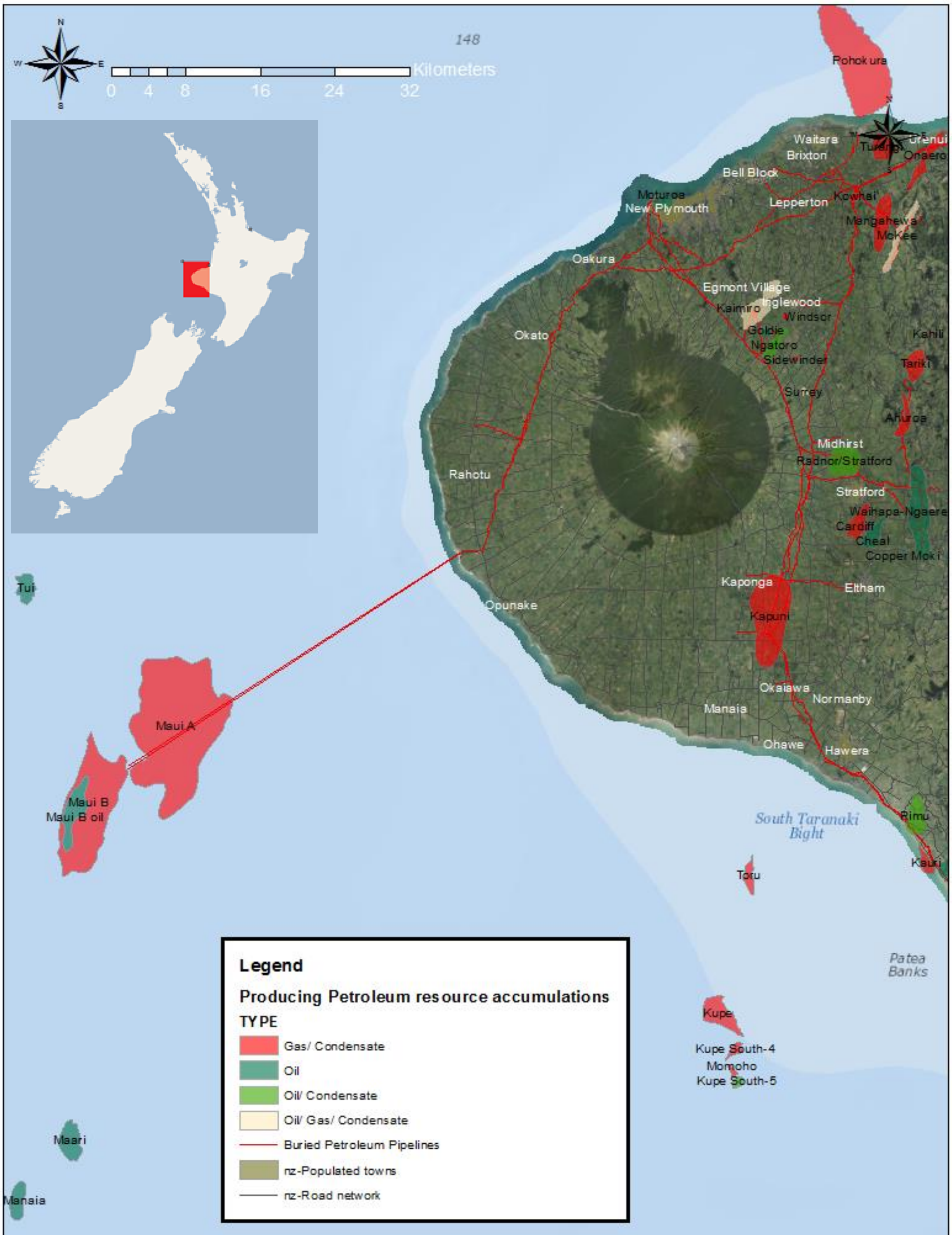

Figure 1.5 Location of New Zealand's producing oil and gas fields (red- gas; green-oil; turquoise-oil and condensate) from Petroleum Basin Explorer (GNS Science, n.d.).

With all legislation, regular revisions occur based on new knowledge and improved working practices. Some of the New Zealand's petroleum infrastructures dates to the start of the industry during the 1960's and 1970's. Since that time technology has advanced, which requires ongoing maintenance and rolling upgrades of the infrastructure. Understanding where current risks and vulnerabilities exist allows the petroleum industry to improve planning, long lead time upgrades, and/or legislative changes to occur.

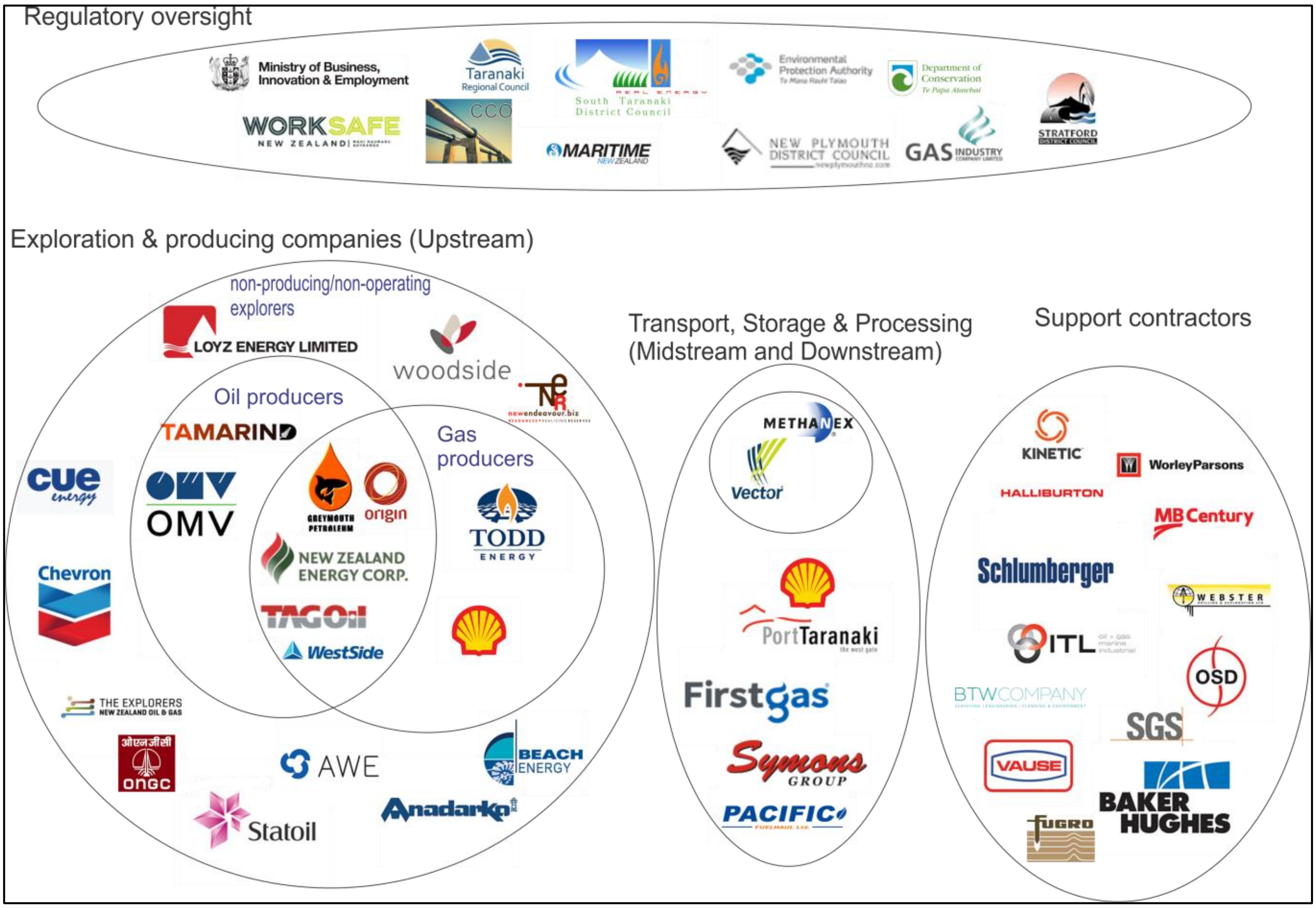

Figure 1.6 Petroleum industry organisation chart, as of June 2017.

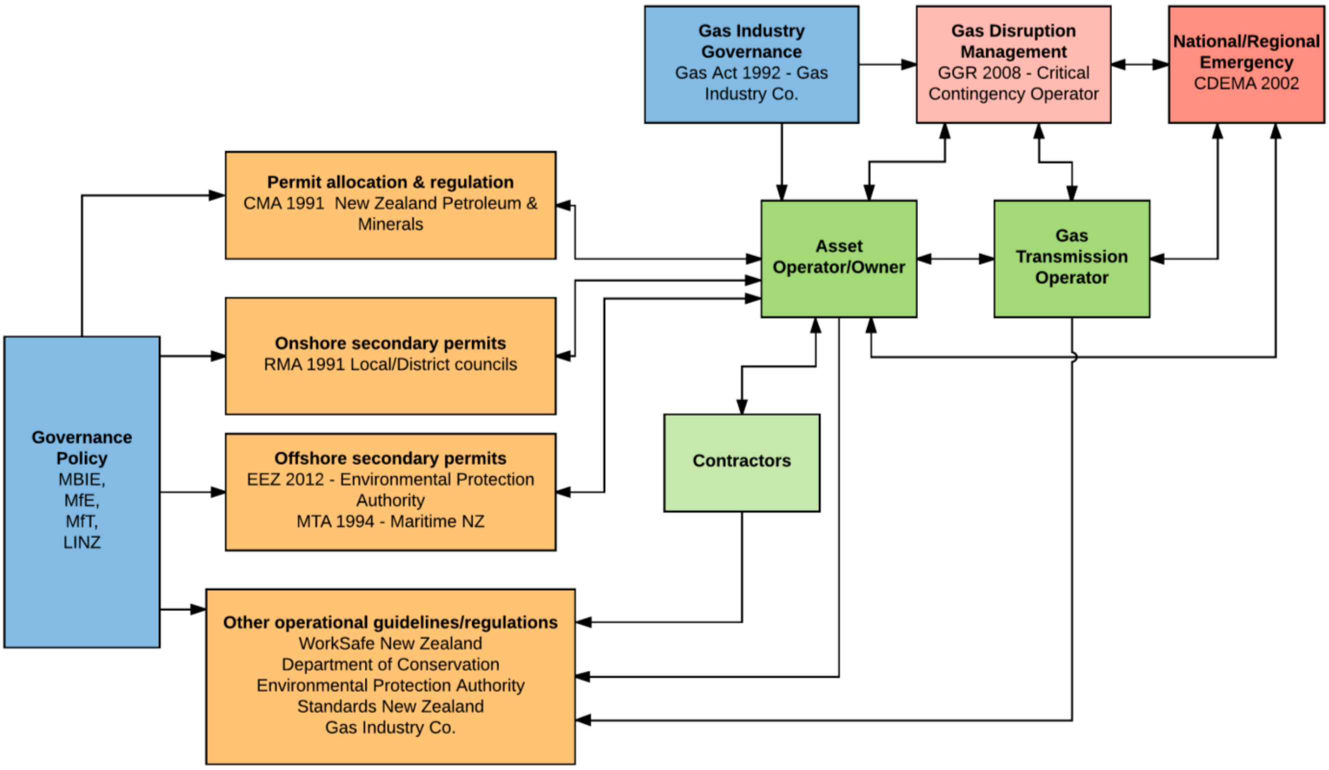

Figure 1.7 Regulatory oversight schematic, see Appendix C (7.0A3.0) for full list and abbreviation guide. Blue represents legislation, Orange the regulating agencies, red the emergency management sector and green are private companies.

1.4.2 Volcanic risk assessment for the petroleum sector in New Zealand

For the New Zealand petroleum risk context, the midstream and downstream sectors are included in disaster resilience planning for lifelines; the New Zealand Government has a “National Fuel Plan” and Gas Governance (Critical Contingency Management) Regulations 2008. However, the upstream extraction industry, especially the smaller companies, does not yet have any specific research focus on their resilience to a volcanic eruption. They do have adverse event planning but have not yet undertaken a detailed analysis of volcanic risks individually.

Recent studies have indicated the probability of a future Mt. Taranaki eruption within the next 50 years is much higher than previously anticipated. A variety of methodological approaches provide a range of eruption probabilities between 33% and 52% (Damaschke, Cronin, & Bebbington, 2017; Turner, 2008; Turner, Bebbington, Cronin, & Stewart, 2009); with one isolated reference inferring an 81% probability of unrest in the next 50 years (Green et al., 2013). A reawakening event of any size will likely impact the entire New Zealand upstream petroleum sector both directly and indirectly. Direct impacts may include ash fall, lahar damage to the pipeline, while indirect impacts such as helicopter grounding, road closures and electricity outage may prevent production, transportation of products and staff availability. If Taranaki’s oil and gas production stopped or products cannot be distributed due to lengthy volcanic activity or damaging impacts, the knock-on consequences present a critical risk for both the Taranaki region and New Zealand. The Egmont National Park around the Mt. Taranaki slopes, out to proximately 12 km, has prevented the development of any industrial or petroleum resource extraction within its boundaries. Volcanic hazard risk assessments have not previously occurred in detail by the New Zealand upstream petroleum sector, due to a perception of an unlikely, remote or hypothetical risk (WorleyParsons, 2014). However, the seismic risk assessments are commonplace for the petroleum sector globally (Gehl, Desramaut, Réveillère, & Modaressi, 2014; Kongar et al., 2016; Urlainis, Shohet, & Levy, 2015). Research acknowledges the existence of a volcanic risk to the petroleum sector in New Zealand, and studies provide estimates of regional economic impacts (Chapman, Bebbington, Cronin, & Turner, 2007; Cronin, 2012; Hull, 1996; Johnston et al., 2011; McDonald et al., 2017; Taranaki Civil Defence & Emergency Management, 2015).

Past experiences of gas supply disruption led to the development of emergency planning revisions and an end user curtailment banding for gas dependent users (Table 1.2) and comprehensive communications plan, overseen by the Critical Contingency Operator. Scenarios for the contingency planning, have tended to be single failure points with a focus on rapid restoration and communication. These plans assume continued production of gas supplies and have not considered volcanic hazards are impacting the entire petroleum sector. Four of the five largest gas users are also based close to the Mt. Taranaki:

- TCC Power Stations,
- Methanex NZ Ltd (Methanol plants),
- Balance Agri-Nutrients (Kapuni) Ltd (fertiliser),
- Fonterra's Te Rapa dairy factory (Critical Contingency Operator, 2017).

Other gas dependants include hospitals, residential care facilities, prisons, crematoriums and bio-hazard treatment facilities. Domestic users do not get impacted by the curtailment banding and will be the last to be impacted if gas supplies become exhausted. No equivalent local dependent users exist for the New Zealand extracted oil supplies as this resource is exported to overseas markets.

Table 1.2 Gas Curtailment bands for New Zealand (Critical Contingency Operator, 2017).

Curtailment Band	Consumption	Consumption Description
0	N/A	Gas used for injection into storage
1	More than 15TJ per day	Consumers supplied directly from the transmission system and that have an alternative fuel capability.
2	More than 15TJ per day	Consumers supplied directly from the transmission system and that do not have an alternative fuel capability.
3	More than 10TJ per annum and up to 15TJ per day	Large industrial and commercial consumers
4	More than 250 GJ per annum and up to 10 TJ per annum	Medium industrial and commercial consumers
5	More than 2TJ per annum	Consumers with essential services designations
6	250 GJ or less per annum	Small commercial consumers
7	Any	Consumers with critical care designations

With a high likelihood of a future Mt. Taranaki eruption and the Taranaki Region's critical lifeline network, it is a convenient time to investigate the potential volcanic hazards and their impacts on this upstream petroleum sector. Petroleum companies need to enhance and review their risk management approaches to volcanic hazards to reduce the volcanic risk to acceptable levels or "as low as reasonably practicable" (ALARP) (WorleyParsons, 2014). This thesis enables the petroleum sector to begin this risk review process. New Zealand is a unique example of where upstream petroleum sector and an active volcano co-exist providing a valuable case study. However, in time as petroleum reserves are sought in more technically challenging areas or with new or reawakening volcanism, this coexistence of the petroleum sectors and volcanic hazards will become a more significant issue for the petroleum sector globally.

1.5 Conceptual Framework

The risk assessment framework provides a systematic and robust method of conducting hazard risk assessments, including volcanic risk assessments. This framework is set out in guidelines from the United Nations for global DRM best practice (UNISDR, 2017). The risk assessment framework combines hazard, exposure and vulnerability and is applicable for both single and multiple hazards (Marzocchi, Garcia-Aristizabal, Gasparini, Mastellone, & Di Ruocco, 2012). An example of its application was the volcanic risk assessment of critical infrastructure in Auckland, New Zealand (Blake, 2017; Deligne, 2016; Deligne et al., 2017; Johnston et al., 2004; G. Wilson et al., 2014). New Zealand's risk management standards also follow global risk management processes (Standards Australia & Standards New Zealand, 2009). The relationship between the volcanic hazard risk assessment framework and New Zealand's risk management framework is presented in Figure 1.9.

1.5.1 Risk context

The New Zealand petroleum sector has not previously considered the volcanic risk for the upstream sector, while some downstream (fuel distribution) has been impacted and considered in risk studies. The petroleum sector in New Zealand incorporates two critical lifeline services, gas and fuel, where previously consideration in risk assessments was for the transmission and distribution (mid and downstream) aspects of the sector (Section 1.4.2.) and overlooked the upstream sector. The upstream sector has been overlooked as many volcanic risk assessments have focused on Auckland, where no upstream petroleum sector exists, therefore out of scope for these projects (Deligne, 2016). This gap is identified in this thesis and addressed through the volcanic risk assessment, where the context for this research considers New Zealand's gas supply and associated upstream petroleum sector. This thesis considers the direct physical impact explicitly on infrastructure and the petroleum sectors' ability to continue to function. Additionally, indirect impacts are considered that relate to the operational functionality of the petroleum sector.

For the risk assessment framework, a high-level holistic systems approach is used for the petroleum industry. Figure 1.8 gives the various levels of detail that volcanic risk assessments can consider, adapted from an example for the electricity supply network using volcanic hazard vulnerability assessments in Auckland, New Zealand (G. Wilson, 2015). The holistic approach was used as this is the first known attempt to systematically assess volcanic impact and risk to the Taranaki petroleum sector, and considering the range and variation in components, companies, and sites. Additionally, this sector is very competitive, and more detailed component level studies would compromise disclosure agreements and confidential information.

Close partnership with a group of core petroleum industry representative organisations is fundamental the success of the framework as per best practice (Standards Australia & Standards New Zealand, 2009b). This was achieved through engaging the industry stakeholders in scoping the project and engaging them throughout the process including the review stage of the final thesis. Additionally, communicating the project and results at petroleum industry and lifeline sector conferences and to the Taranaki civil defence community.

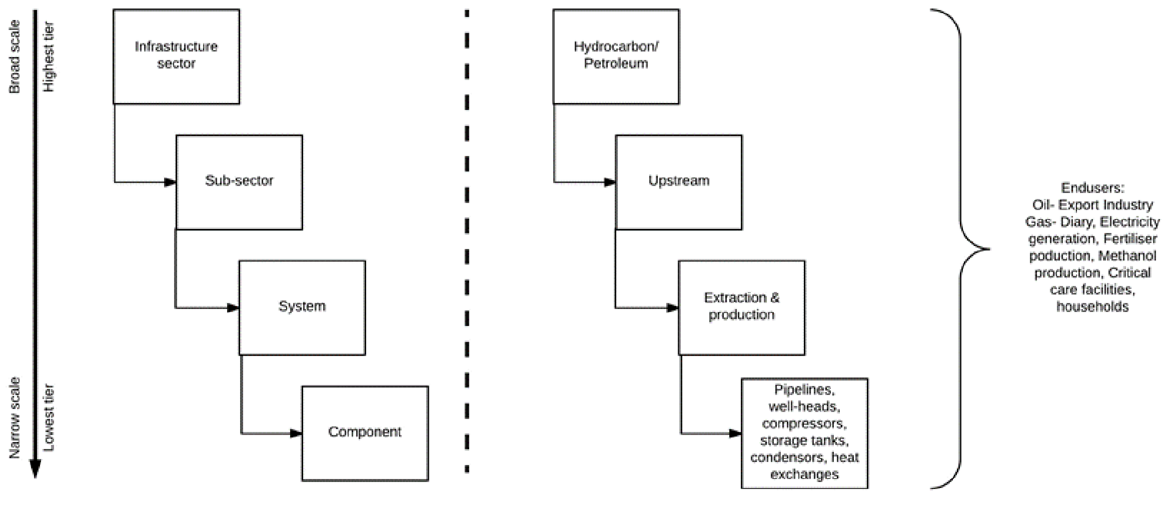

Figure 1.8 Critical infrastructure tier scheme for the petroleum sector adapted from G. Wilson (2015).

1.5.2 Risk identification

Impact and risk understanding that hazards pose to humans considers a variety of aspects, including social, natural, economic, built, and cultural environments (Coppola, 2011). The risk identified for this research considers the volcanic hazards and how the characteristics of those hazards will impact the physical assets of the petroleum sector, both directly and indirectly. The Taranaki region was considered as a case study, applying the methodology developed. The project scope was identified, documented and justified at each step of the risk assessment framework, noting where exclusions, inclusions or limitations are imposed or encountered.

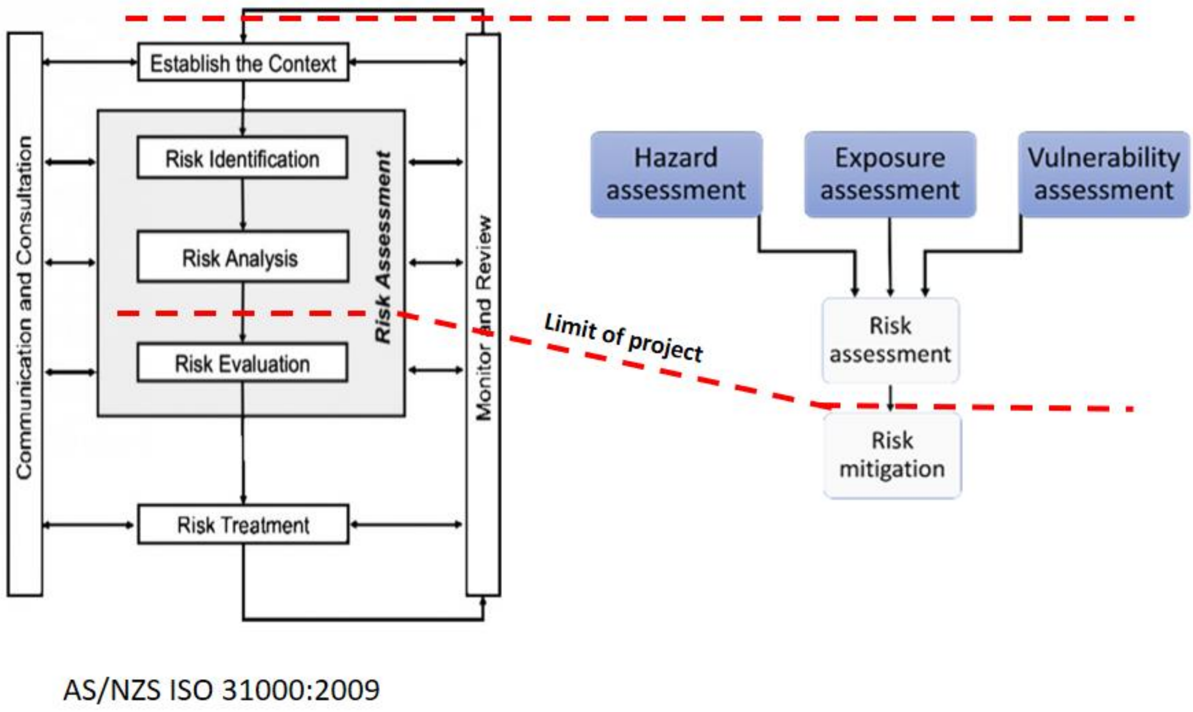

Figure 1.9 Relationship between the Australian and New Zealand risk management process (left) and the UN natural hazard risk assessment framework (right).

1.5.3 Risk analysis

"Risk analysis is the process of comprehending the nature of risk and to determine the level of risk" (Standards Australia & Standards New Zealand, 2009, p. 5).

Volcanic risk assessment frameworks combine hazard, exposure and vulnerability assessments in the risk analysis (UNISDR, 2017). A hybrid or mixed methodological approach is used for the hazard, exposure and vulnerability assessments of the petroleum sector. Hybrid or mixed methodological approaches combine theoretical, expert-judgement or analogues from recent eruptions to anticipate impacts from future eruptions on infrastructure. Examples include the study of future eruptions of the Auckland volcanic field in New Zealand (Blake, 2017; Deligne et al., 2017; Houghton et al., 2006; Johnston et al., 2004). The hybrid approach has the advantage of reducing uncertainties through combining different approaches (G. Wilson et al., 2017). A hybrid or mixed methodological approach for the risk assessment framework is particularly useful when a void of empirical data or numerical modelling exist, as is the case when considering volcanic hazard impacts on the petroleum sector.

The UN guidelines outline that the risk assessment framework should include:

- Probabilistic analysis – the modelling of many possible scenarios, their likelihood and related impacts. This approach relies on the development of complex mathematical behaviour models for each hazard, using past eruption data, historical losses, or damage data. This approach is also the most useful for comparison of multiple sectors, hazards or risks.

- Deterministic or scenario analysis – the modelling of impacts or losses from a single scenario. This approach considers one of many scenarios, and multiple scenarios are recommended to cover the variety of possibilities. The results enable improved resilience when incorporating broad scenarios.

- Historical analysis - empirical data from past events is compiled over an extended period to derive trends and frequency information, and potential impacts data. This method requires reliable data and extensive databases of frequently occurring events.

- Expert elicitation – this approach is used where no knowledge or data of past events are available and draws on expert judgement to provide quantitative perspectives on risk. However, this comes with a level of uncertainty.

The risk assessment framework follows the consistent approach demonstrated by G. Wilson et al. (2014), and a limited deterministic approach was applied for the Mt. Taranaki due to the limited probabilistic hazard modelling available.

1.5.4 Risk treatment

The limit of the research stops short of risk evaluation and treatment processes. The Standards guideline states risk evaluation as "the process of comparing results of risk analysis with risk criteria to determine whether the risk and its magnitude is acceptable or tolerable" (Standards Australia & Standards New Zealand, 2009, p. 6). It is not for the author to make this determination, but the industry either together or individually to determine their level of acceptable or tolerable risk and what mitigation or risk reduction methods they will consider in the future. This research will give examples of possible risk reduction options, noting that these are not comprehensive or necessarily suitable for all assets or locations.

1.6 THESIS STRUCTURE

This thesis has six core chapters, with the final chapter summarising the key findings and how they relate to the original thesis aims and making recommendations for future work. Within Chapters 2, 3 and 4 the scope of the project is documented and justified, noting where exclusions, inclusions or limitations are imposed or encountered.

- Chapter 2 characterises the volcanic hazard to the petroleum sector from Mt. Taranaki. It achieves this by reviewing the published research of past eruptive events from hazard assessments of analogous volcanoes and considering ongoing volcanic hazard assessment research. The second part of the chapter uses this review to inform the development of two eruption hazard scenarios, which is used for undertaking a risk assessment in Chapter 4 (addressing Objective 1 of the thesis).

- Chapter 3 identifies and categorises the petroleum sectors physical assets that will be exposed to volcanic hazards from future Mt. Taranaki eruptions. The chapter describes the methodology used to develop asset inventory, details and maps how they link together into a system and categorises the functional utility of the assets (addressing Objective 2 of the thesis). The compiled asset inventory, system maps and asset categorisation directly inform the risk assessment framework within Chapters 4 and 5.

- Chapter 4 presents the development of vulnerability models for the physical assets of the petroleum sector for application in a volcanic risk assessment (Chapter 5). The vulnerability assessment uses a mixed methodology that includes a literature review and expert elicitation to develop theoretical vulnerability matrices the petroleum sector. These vulnerability models build on the hazard and exposure assessments developed in Chapters 2 and 3, for use in the risk assessment for the petroleum sector to volcanic hazards in Chapter 5 (fulfilling Objectives 1 and 2 of the thesis).

  Chapter 5 develops and applies a volcanic risk assessment to the Taranaki petroleum sector for the physical assets. The risk assessment uses a deterministic approach, combining the hazard scenarios developed in Chapter 2, the asset inventory from Chapter 3, and the vulnerability models from Chapter 4, for the Taranaki petroleum sector (fulfilling Objectives 1 and 2). Uncertainties captured in the application of the risk assessment framework for the Taranaki petroleum sector are addressed in this chapter. Additionally, dependencies on other lifelines and systems are investigated using expert elicitation, and a list of critical dependencies is derived for the Taranaki petroleum sector.

- The final Chapter of the thesis (Chapter 6) concludes by summarising the key findings and how they relate to the original thesis aims. It also contains recommendations for future work, which may result in the development of a volcanic risk assessment framework for the petroleum sector and application to the Taranaki sector.

The content of all chapters in this thesis directly results from my research and studies, under the guidance of my supervisory team and with close partnership and collaboration with the petroleum sector. Those who assisted with the work are recognised in the acknowledgements; attendees of the expert elicitation workshop are listed in Appendix E (7.0A5.0).

2.0 VOLCANIC HAZARDS OF THE MT. TARANAKI FOR THE PETROLEUM SECTOR

2.1 INTRODUCTION

This chapter characterises the volcanic hazard to the petroleum sector from Mt. Taranaki. It achieves this by first reviewing published research of past eruptive events, hazard assessments, and hazard modelling of Mt. Taranaki, and analogous volcanoes. The second part of the chapter uses this review to inform the development of two eruption hazard scenarios, which are used for undertaking a risk assessment in Chapter 5 (addressing Objective 1 of the thesis).

2.2 VOLCANIC HAZARDS ASSESSMENT

Undertaking a volcanic risk assessment first requires the development of a volcanic hazards assessment (UNISDR, 2017). The objective of a volcanic risk assessment is to understand the eruptive style, size and frequency of volcanoes and is achieved by examining the geological record and volcanoes with similar eruptive styles (Sparks et al., 2012). The outputs of a volcanic hazard assessment often take the form of maps, event trees and hazard scenarios to represent the range and footprint of the hazards from the studied volcano (Sparks et al., 2012). These outputs inform risk specialists, emergency managers and policymakers, and aid decision making in planning and mitigating for future volcanic eruptions.

There are several volcanic hazard assessment approaches from literature, which can be used when investigating a study volcano, a list is compiled below (McBirney & Godoy, 2003; Neri et al., 2008; Sparks et al., 2012):

- review historical records and oral history
- undertake geological mapping of volcanic deposits and past events to determine hazard sizes and footprints
- undertake geophysical modelling
- undertake geochemical studies
- undertake chrono-lithostratigraphic studies to characterise the frequency of events
- model volcanic hazard processes
- identify and study analogous events

In many cases, existing studies have been undertaken to address the above. In cases without existing knowledge, geological mapping and geophysical and geochemical surveys will identify the types of hazards associated with the volcano (McBirney & Godoy, 2003). Once the types and nature of hazards have been determined using available data, the following outputs can be developed:

- zonation, hazard or exposure maps including the location of communities
- logic or event trees - these include Bayesian event trees that include probabilities
- evaluate the eruption magnitude or hazard intensity metrics for volcanic hazards
- eruption hazard scenarios

2.2.1 Mt. Taranaki hazard assessment

The hazard assessment of Mt. Taranaki compiles the identification of the likely style, size and eruption hazards for future Mt. Taranaki eruptions from published literature. Previous studies which assess the volcanic hazards from Mt. Taranaki detail existing geological, geophysical and geological mapping, chrono-lithostratigraphic studies, modelling for a limited range of hazards, and a zonation map (Alloway et al., 2005; Alloway et al., 1995; Cronin, Stewart, Neall, Platz, & Gaylord, 2003; Damaschke, Cronin, Holt, et al., 2017; Della-Pasqua, Massey, McSaveney, & Townsend, 2016; Neall & Alloway, 1996; Neall et al., 1986; Platz, Cronin, Cashman, Stewart, & Smith, 2007; Platz, Cronin, Procter, Neall, & Foley, 2012; Procter et al., 2010; Torres-Orozco, Cronin, Pardo, & Palmer, 2017; Turner, Cronin, Smith, Stewart, & Neall, 2008; Zernack, Cronin, Neall, & Procter, 2011). Similar volcanoes are examined, which help inform future eruption sizes and styles for Mt. Taranaki.

Within the last 30,000 years, evidence has identified over 228 tephra-producing eruptions, with deposits located at distances up to 270 km from the volcano (Damaschke, Cronin, Holt, et al., 2017). These studies indicate Mt. Taranaki has a cyclic behaviour with prolonged periods of eruptive cycles and quiescent periods and sector collapses, shown in Figure 2.1 (Turner, Cronin, Bebbington, Smith, & Stewart, 2011; Turner, Cronin, Smith, et al., 2008; Zernack et al., 2012; Zernack et al., 2011; Zernack, Procter, & Cronin, 2009). Mt. Taranaki has two dominant eruption styles: smaller effusive eruptions are more common, where periods of dome building and collapse are dominant, interspersed with less frequent larger sub-Plinian (explosive) eruptions (Alloway et al., 1995; Damaschke, Cronin, Holt, et al., 2017). The small effusive eruptions represent 80% of the known eruptions in the last 30,000 years, with an annual probability of 0.03, while the larger explosive eruptions represent the remaining 20% of eruptions have an annual probability range of 0.010-0.015 (McDonald et al., 2017; Turner et al., 2011). Additionally, sector collapses have occurred at least 18 times in the past 30,000 years and are likely to occur again with an annual probability of 0.00018 (Damaschke, Cronin, Holt, et al., 2017; Della-Pasqua et al., 2016; McDonald et al., 2017; Zernack et al., 2012; Zernack et al., 2011). Studies of the larger eruptions indicate Mt. Taranaki eruptions can include multiple eruptive styles from effusive to explosive, that are related to internal changes in magmatic factors such as the rate of magma ascent, volume, or dyke formations (Platz et al., 2007).

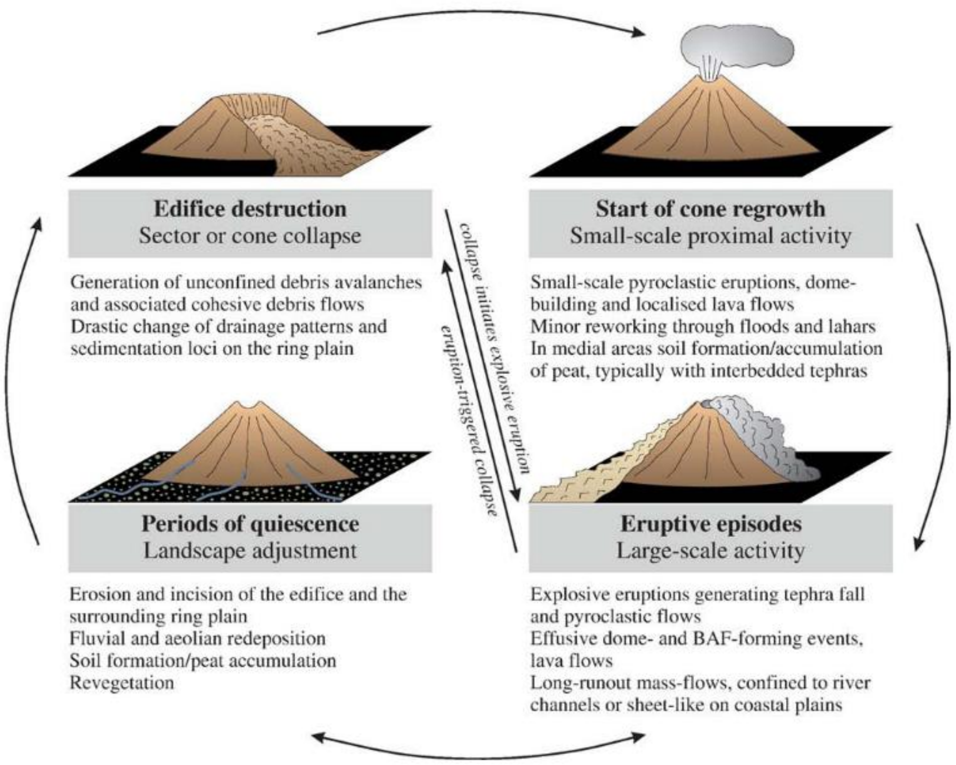

Figure 2.1 Diagram of Mt. Taranaki eruptive cycle from Zernack et al. (2009).

The previous research and mapping of the geology of volcanic deposits in the Taranaki region have been used to inform the existing hazard maps, primarily based on the hazard types and footprints of past eruptions(Neall & Alloway, 1993; Neall & Alloway, 1996). Figure 2.2 is a simplified version of the volcanic hazard map of Mt. Taranaki, with hazard zones outlined.

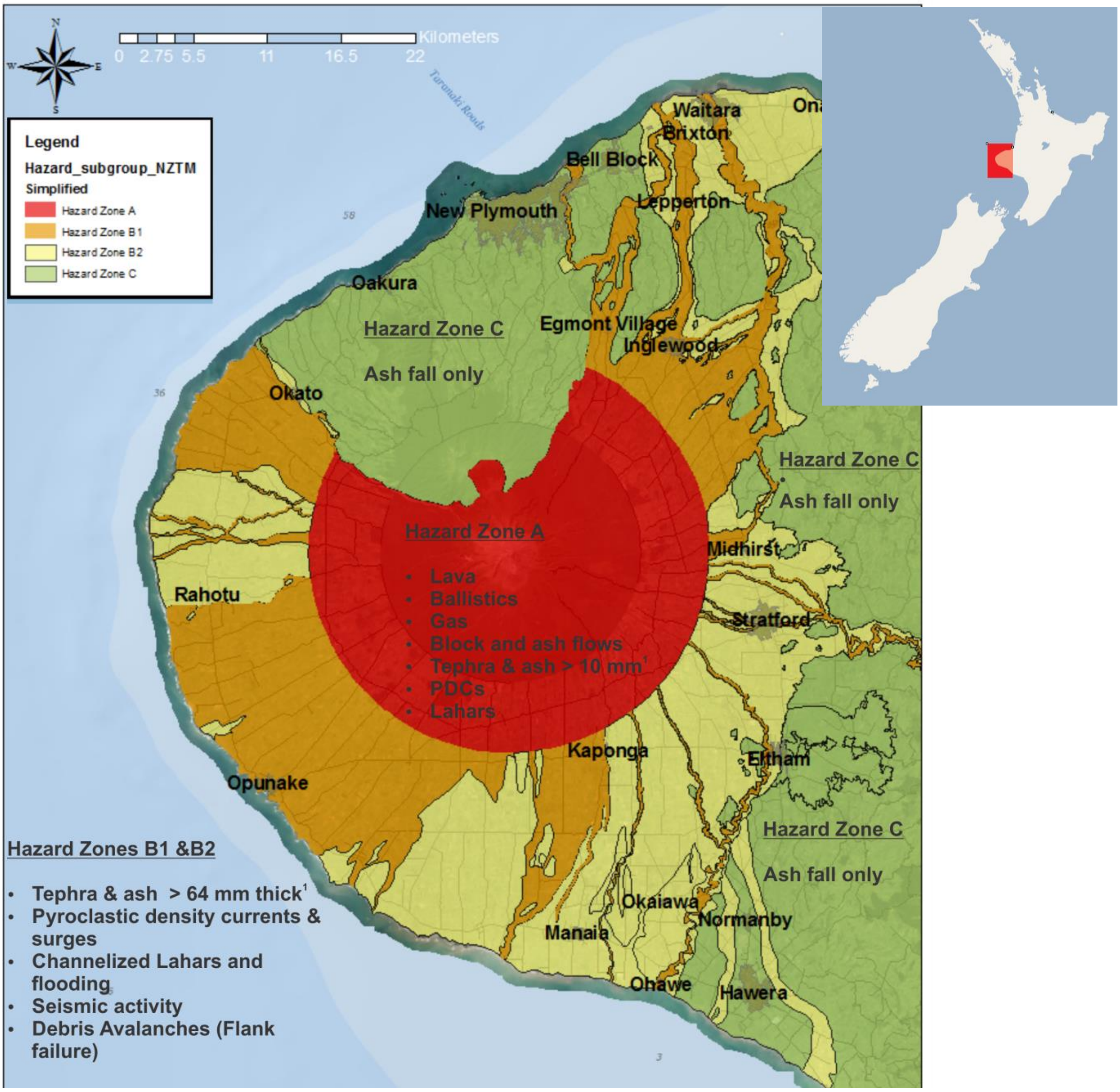

Figure 2.2 Volcanic Hazards of Taranaki simplified from (Neall & Alloway, 1996). Annotations of ash thickness are from the probabilistic modelling of ashfall for larger eruption sizes by Hurst and Smith (2010). Insert map of New Zealand showing the location of the Taranaki Region.

Table 2.1 is a compilation of the literature review undertaken for Mt. Taranaki for future Mt. Taranaki eruptions. An important part of this thesis has been to compile a concise list of volcanic hazards from past Mt. Taranaki eruptions. A review of the published literature provided a list of known hazards, a brief description, and the distance ranges that the hazard will likely impact. Analysis of these was combined with the bounding factors (Section 2.2.2) to determine if the hazard is applicable to the petroleum sector in Taranaki and thus required (included) for the vulnerability and risk assessments (Chapters 4 and 5). The final column of the table provides a list of references used in the literature review.

2.2.2 Bounding factors and scope of hazard assessment

An important part of this thesis has been to identify and set the boundaries of the study scope. Identifying the geological extent and hazards applicable to the petroleum sector is a key step in defining the scope of the hazard assessment and any bounding limits. Bounding factors applied to this hazard assessment are discussed below: they define the limitations of the thesis and scope of the case study.

The initial bounding factor applied to this thesis is to consider "above-ground" assets and impacts only. Therefore, subsurface volcanic hazards are not considered, such as heat flow associated with magmatic intrusions. Magmatic intrusions have a limited heat flow range where rocks are metamorphically altered (Mathieu, van Wyk de Vries, Holohan, & Troll, 2008; Polteau, Mazzini, Galland, Planke, & Malthe-Sørenssen, 2008), which are unlikely to impact the petroleum reservoirs 13 km away from Mt. Taranaki and at depths of 2.5 km or greater.

Hazards that occur within a 12-km radius of the summit are excluded, due to the existence and restrictions of the Egmont National Park. The park provides a 12-km bounding factor that is applied to Mt. Taranaki, as these hazards will not impact petroleum assets that are prohibited within the park. The hazards excluded due to distance include lava, volcanic gases and near-vent hazards. Volcanic gases generate acid rain when combined with water, which causes erosion and corrosion of infrastructure (Johnston et al., 2011). While volcanic gases disperse over long distances, the concentration beyond 12-km is unlikely to cause immediate physical damage to petroleum assets but may cause short-term disruption from gas monitoring sensor alerts or more regular maintenance of assets in the longer term.

A review of published work found limited probabilistic modelling of hazards outside the 12-km National Park extent, with some limited ashfall modelling (Hurst & Smith, 2010; Wild, 2016). Ash modelling used TEPHRA2 and the New Zealand Probabilistic Volcanic Hazard Model to estimate the likelihood of ash deposits from the statistically most dominant regional wind directions. Limitations of these models include local variations in the weather, as the weather of Taranaki is known to be highly changeable. A small sampling of forecasts by GNS over a period of a few days in 2017, shows how variable the wind direction is, see Appendix D (7.0A4.0). GNS currently uses the ASHFALL model, with development underway to change to HYSPLIT modelling, to generate ashfall forecasts on a daily basis (Hurst, 1994; Hurst & Davis, 2017).

Associated with volcanic unrest and eruptions are seismic hazards, where frequent small earthquakes, are caused by the mobilisation of magma below the ground. As the pressures inside the magma chamber and vent increase in the weeks and months before an eruption, the seismic activity increases giving warning of a potential eruption, as seen in the 2017 Agung Volcano eruption (Normile, 2017). Seismic magnitudes associated with volcano seismicity tend to be less than magnitude 4 (Sigurdsson et al., 2015). Seismicity starts small and unnoticeable to humans and increases as the magma approaches the surface where the buried rock is more brittle, producing larger earthquakes or volcanic tremors associated with the eruption (Sparks, 2003). However, some eruptions give little to no warning, for example, the phreatic eruption of Ontake Volcano, Japan in 2014 (Ogiso, Matsubayashi, & Yamamoto, 2015). New Zealand has advanced seismic risk codes for critical infrastructure which should mitigate the effects of most volcanic earthquakes (Standards New Zealand, 2004; Stirling et al., 2012); it was decided to exclude this hazard from the research.

Table 2.1 Compilation of possible volcanic hazards for Mt. Taranaki, see text in Section 2.2.3 for discussion on excluded hazards.

Hazard	Description	Impact Range	Included/ excluded	References
Ashfall	The larger tephra particles fall out of the plume within the 10-km boundary line of the National Park. While the small ashfall will fall in directions and distance that are heavily influenced by the wind at the time. Additionally, the static load increases if ash accumulations become water saturated.	100's km	Included	(Blong et al., 2017; Damaschke, Cronin, Holt, et al., 2017; Deligne & Wilson, 2015; Hurst & Smith, 2010; Jenkins, Magill, McAneney, & Blong, 2012; Jenkins, McAneney, Magill, & Blong, 2012; Jenkins, Wilson, et al., 2014)
Lahar (& flooding)	Lahars can include both hot and cold lahars. The high rainfall in the Taranaki region adds to the hazard. These can occur during and post-eruption and can continue for many decades after the eruption.	10's km	Included	(Damaschke, Cronin, Holt, et al., 2017; Deligne & Wilson, 2015; Neall, 2011; Procter, Cronin, & Zernack, 2009; Zernack et al., 2011; Zernack et al., 2009)
Lava	Mt. Taranaki's andesitic lava has a limited flow range	7-10 km	Excluded	(Deligne & Wilson, 2015; Neall & Alloway, 1993)
Near-vent hazards	Including ballistics, lateral blasts, new edifices & atmospheric phenomena	5-7 km	Excluded	(Deligne & Wilson, 2015; Neall & Alloway, 1993)
PDC	Occur during both small and large eruptions, with larger eruption PDCs travelling further distances. Note fringe properties are not as intense as the primary zone.	10's km	Included	(Brown, Loughlin, Sparks, & Vye-Brown, 2014; Cronin et al., 2003; Deligne & Wilson, 2015; Jenkins et al., 2013; Neall & Alloway, 1993; Platz et al., 2007; Procter et al., 2010).
Sector collapse	Large collapse of the volcano sides producing debris avalanches over a wide area related to the direction of the sector that fails,	10's km	Included	(Della-Pasqua et al., 2016; Procter et al., 2009; Zernack et al., 2012; Zernack et al., 2011)
Seismicity	Volcanic earthquakes, swarms and volcanic tremors	10's km	Excluded	(Hurst, Jolly, & Sherburn, 2014)
Volcanic Gases	Volcanic gases can be detected over long distances, with the concentration rapidly decreasing with distance.	10's km	Excluded	(Sigurdsson et al., 2015)

2.3 SCENARIO DEVELOPMENT

Scenario development for the volcanic risk assessment is similar to methods used in assessments other hazards, incorporating best practice methods including the use of geospatial data (UNISDR, 2017). For complex multi-hazard events like volcanic eruptions, an event tree is useful to express the complexity and associated uncertainty (Neri et al., 2008; Newhall & Hoblitt, 2002). Compilation of likely eruption hazard scenarios for the study volcano leads to the development of scenarios for the most likely and worst case. These hazard scenarios may come from existing hazard scenarios already undertaken for the study volcano or inspired by events in the geological record. The geological mapping informs the development of hazard scenarios based on past events to produce the hazard extent for simplistic models used in deterministic risk analysis. Furthermore, probabilistic hazard analysis hazard scenarios are generated using sophisticated computer-based modelling software. The output hazard scenarios can then be sense-checked through expert elicitation and comparison to analogue eruptions. Computer generated hazard scenarios are also more likely to be able to model the eruption scenarios through time, compared to snap-shot hazard scenarios that represent a final accumulation following many hours/days or even weeks of an eruption.

2.3.1 Mt. Taranaki case study

For the Mt. Taranaki case study, two eruption hazard scenarios have been developed for the application of the risk assessment framework to the petroleum sector in Taranaki in Chapter 5. A deterministic approach for the hazard assessment is used for the Taranaki case study as there is insufficient probabilistic data available for Mt. Taranaki hazards that will impact the petroleum sector. Additionally, the hazard scenarios are simple for the expert elicitation workshop attendees and partner organisations to understand the impacts of a future Mt. Taranaki eruption. The two hazard scenarios developed to represent the most likely and maximum credible eruption sizes, but do not provide the full range of potential eruption possibilities at Mt. Taranaki.

For the Mt. Taranaki, the two hazard scenarios are selected from the event tree developed for Mt. Taranaki as part of this thesis (Figure 2.3) and mapped using GIS into a two-dimensional representation of the extent of the volcanic hazards. A Bayesian event tree is not within the scope of this study. The development of this tree draws on published material, similar eruption events, and discussions with GNS Science staff. The process of developing the event tree also allows the non-volcanic sources of a sector collapse to be identified, which could initiate future volcanic activity (Della-Pasqua et al., 2016; Zernack et al., 2012).

For Mt. Taranaki, some eruption events or episodes have received detailed study, and work has been undertaken to fit models to the known geological record. The three eruptions comprehensively studied are Inglewood, Opua, and Tahurangi eruptions (Cronin, 2012; McDonald et al., 2017). The smaller Tahurangi eruption is the basis for CDEM Exercises Taranaki Blowout, 2008 and Exercise Pahu, 2013. The Pahu/Tahurangi scenario represents a small-scale effusive eruption event, producing small debris flows down existing drainage channels to the northwest side of the volcano, new lava, small volumes of tephra and ash, lahars to the northeast and southeast (Jérôme & Neall, n.d.). The Pahu/Tahurangi scenario is chosen in this thesis to represent the most frequent and smaller types of Mt. Taranaki eruptions. Unfortunately, no GIS maps were readily available of the extent of the various hazards produced from these hazard scenarios. A second scenario is required as the

Pahu/Tahurangi scenario represents a very small-scale eruption in comparison to known more massive Mt. Taranaki eruptions known to occur. Analogue examples of the larger Mt. Taranaki eruptions include Calbuco Volcano, Chile, 2015, Redoubt Volcano, Alaska 1989 and 2009, and Mt St Helens Volcano, USA, 1980. These eruptions help inform the development of a new large eruption scenario for Mt. Taranaki, based on the Kahui explosive eruption event of Mt. Taranaki approximately 8.9 ka ago (Zernack et al., 2011). The Kahui scenario was selected to represent the maximum credible Mt. Taranaki eruption and was selected based on the distribution of mapped deposits.

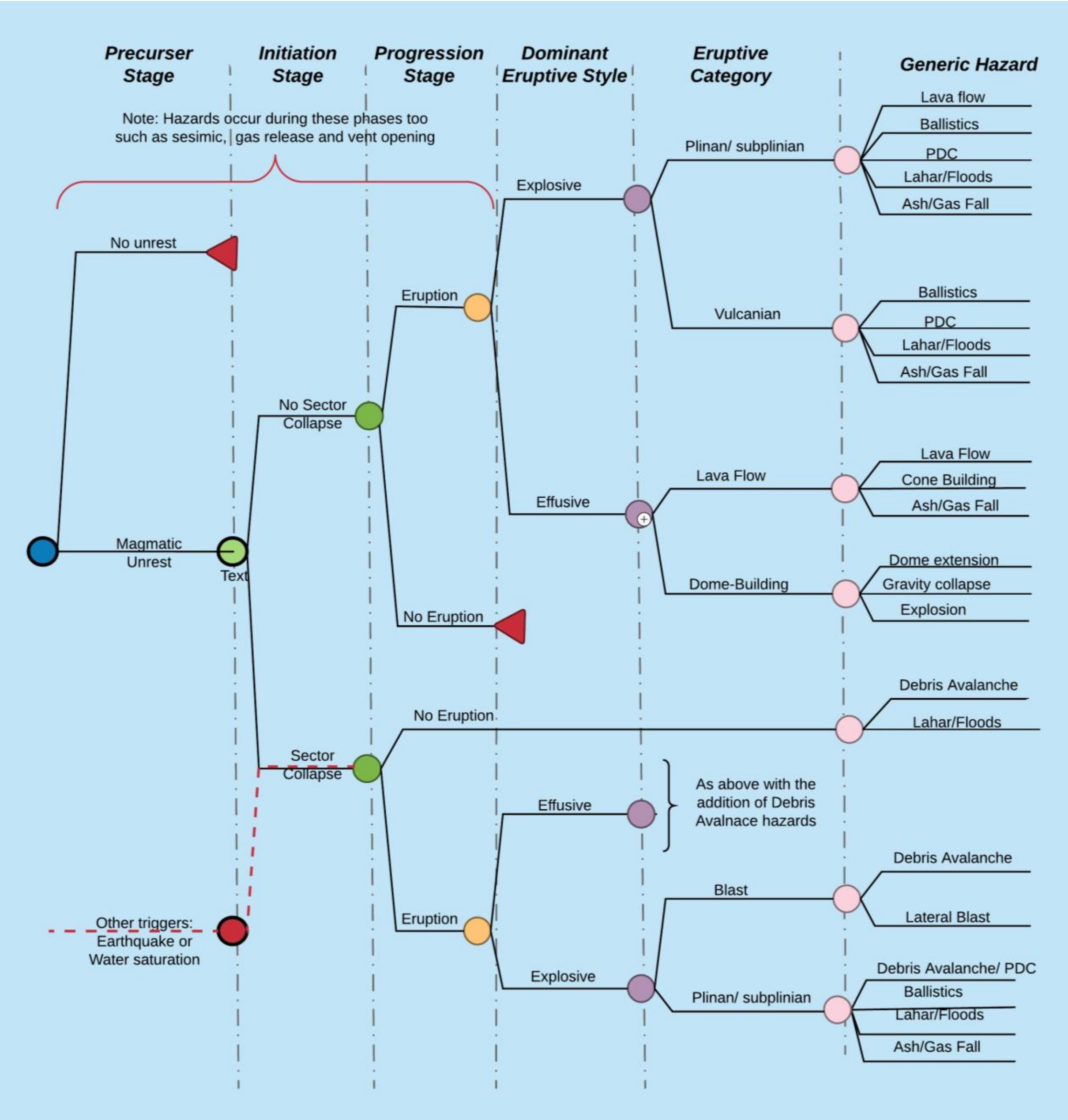

Figure 2.3 Hazard event tree for Mt. Taranaki volcanic eruption events and associated hazards. Colour circles represent stage commencement points; red triangles represent branch terminations.

The scenario development for Mt. Taranaki utilised the GIS version of the existing QMAP (1:250 000 Geological Map of New Zealand) for the Taranaki region (Rattenbury & Isaac, 2012; Townsend, Vonk, & Kamp, 2008). The mapped geological formations were selected based on formations associated with past eruptions provided in Zernack et al. (2011). For each of the hazard scenarios, Ashfall data was imported into ArcGIS from GNS daily forecasts that use the ASHFALL model (Hurst, 1994). Table 2.2 presents the data sources and literature used to develop the two hazard scenarios for Mt. Taranaki. Figure 2.5 and Figure 2.6 show the two-dimensionally mapped hazard scenarios and hazard footprints.

Table 2.2 Mt. Taranaki eruption scenario data sources.

Eruption size	**Geological Eruption**	**QMAP Formations**	**ASHFALL Model**	**Scenario Probability**	**References**
Small Effusive Eruption (VEI 2-3) Vulcanian eruption	Tahurangi eruption	Hangatahua Formation and Peter's lavas	4 km plume, 0.05 km^3 volume using a forecast from 18 September 2017 at 1800	0.010-0.012 annually	(Hurst, 1994; McDonald et al., 2017; Platz et al., 2012; Rattenbury & Isaac, 2012; Torres-Orozco et al., 2017; Townsend et al., 2008; Zernack et al., 2011)
Large Explosive Eruption (VEI 4-5) Sub-Plinian/Plinian	Kahui eruption	Kahui formation and Warwick lavas	15 km plume, 1 km^3 volume using a forecast from 19 September 2017 at 0600	0.03 annually	(Hurst, 1994; McDonald et al., 2017; Platz et al., 2007; Rattenbury & Isaac, 2012; Torres-Orozco et al., 2017; Townsend et al., 2008; Turner, Cronin, Bebbington, & Platz, 2008; Zernack et al., 2011)

2.3.2 Unrest phase for developed hazard scenarios

An unrest timeline was developed for Mt. Taranaki with support from GNS volcanic alert specialist Brad Scott, specifically for the petroleum expert elicitation workshop using the New Zealand Volcanic Alert Levels (VAL) (Figure 2.4) (Potter et al., 2014). The eruption timeline supports the hazard scenarios to visualising how a future Mt. Taranaki eruption will progress and at what point the volcanic hazards occur and examples of the possible impacts of those hazards on the petroleum sector. In the unrest timeline, it is essential stakeholders do not link actions or decisions to the changing of the alert level, as this may lag actual events (Papale, 2017). Experience shows a lot can change and happen between the level changes, and this can happen quickly or gradually over many months (Papale, 2017). Therefore, planned actions should consider situational awareness from many sources and a company's or organisation's ability to sustain the actions it makes. Once an eruption occurs, there will be a period of unrest that follows, which may lead to further eruptions in the following days, weeks or years. Figure 2.4 shows a potential cycle of unrest, with a small eruption followed by a larger eruption, then a post-eruption unrest phase for Mt. Taranaki. The eruption phases (VAL 3 and 4) can be substituted for a single small eruption (VAL 3) or a single large eruption (VAL 4).

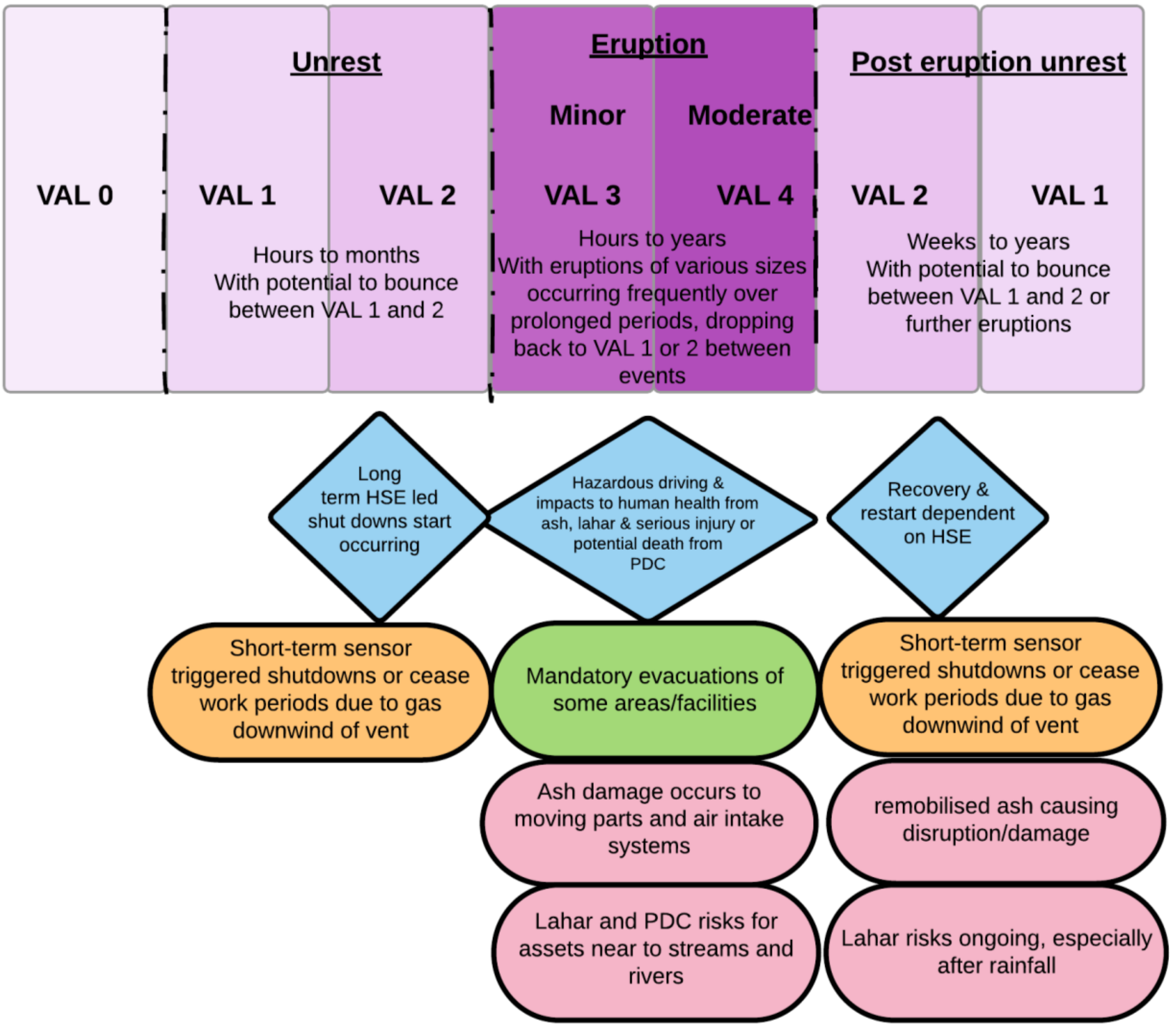

Figure 2.4 Potential future Mt. Taranaki eruption timeline, with possible hazard presence impacts. The VAL colours are aligned to the official VAL (Potter et al., 2014). Blue identify potential HSE concerns, orange- potential short-term disruption to petroleum sector, green – potential evacuation zone impacts, pink – potential physical impacts from volcanic hazards.

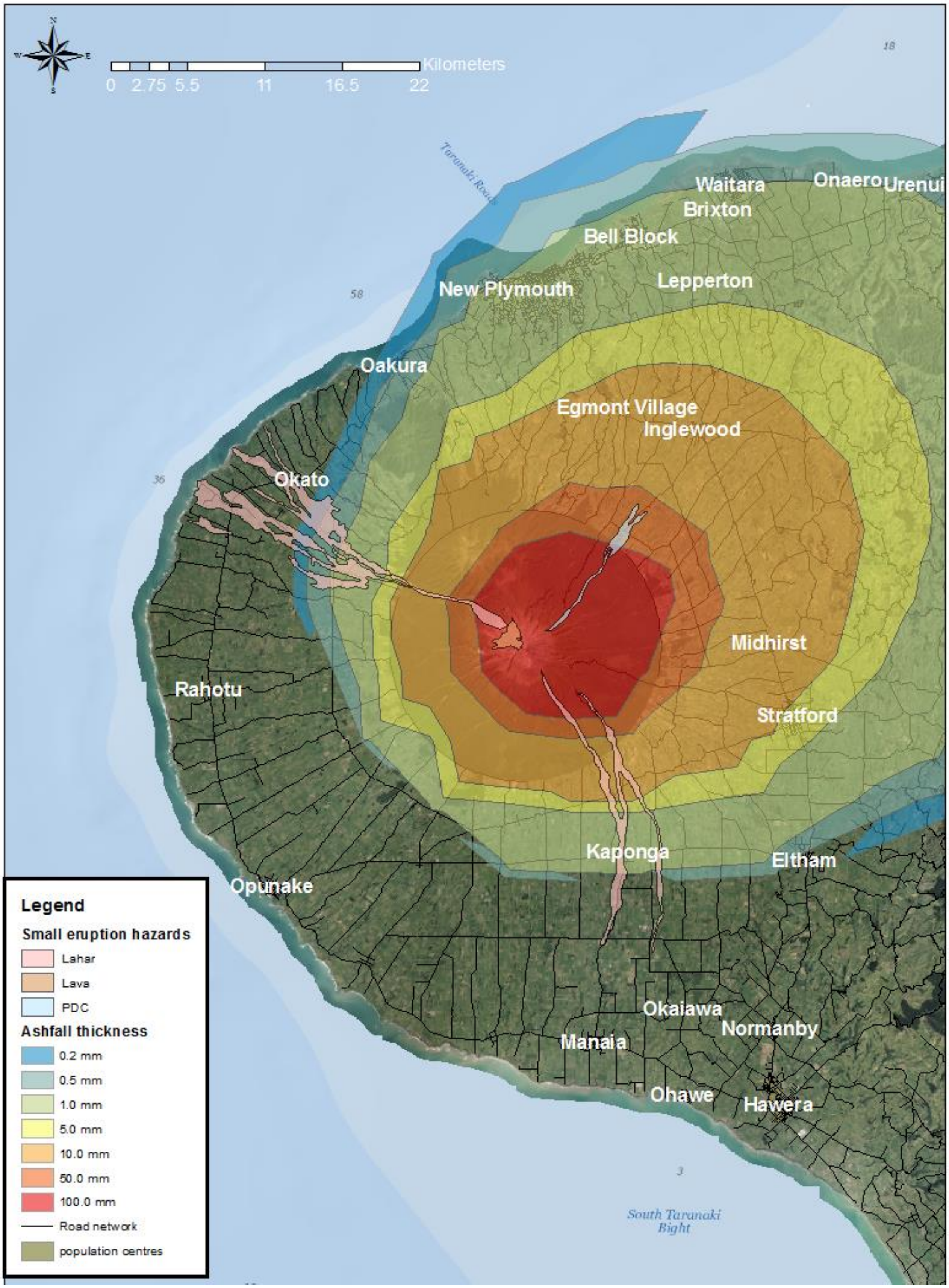

Figure 2.5 Mt. Taranaki - Small eruption scenario using hazard footprints, PDC blue, lahar red, and lava brown.

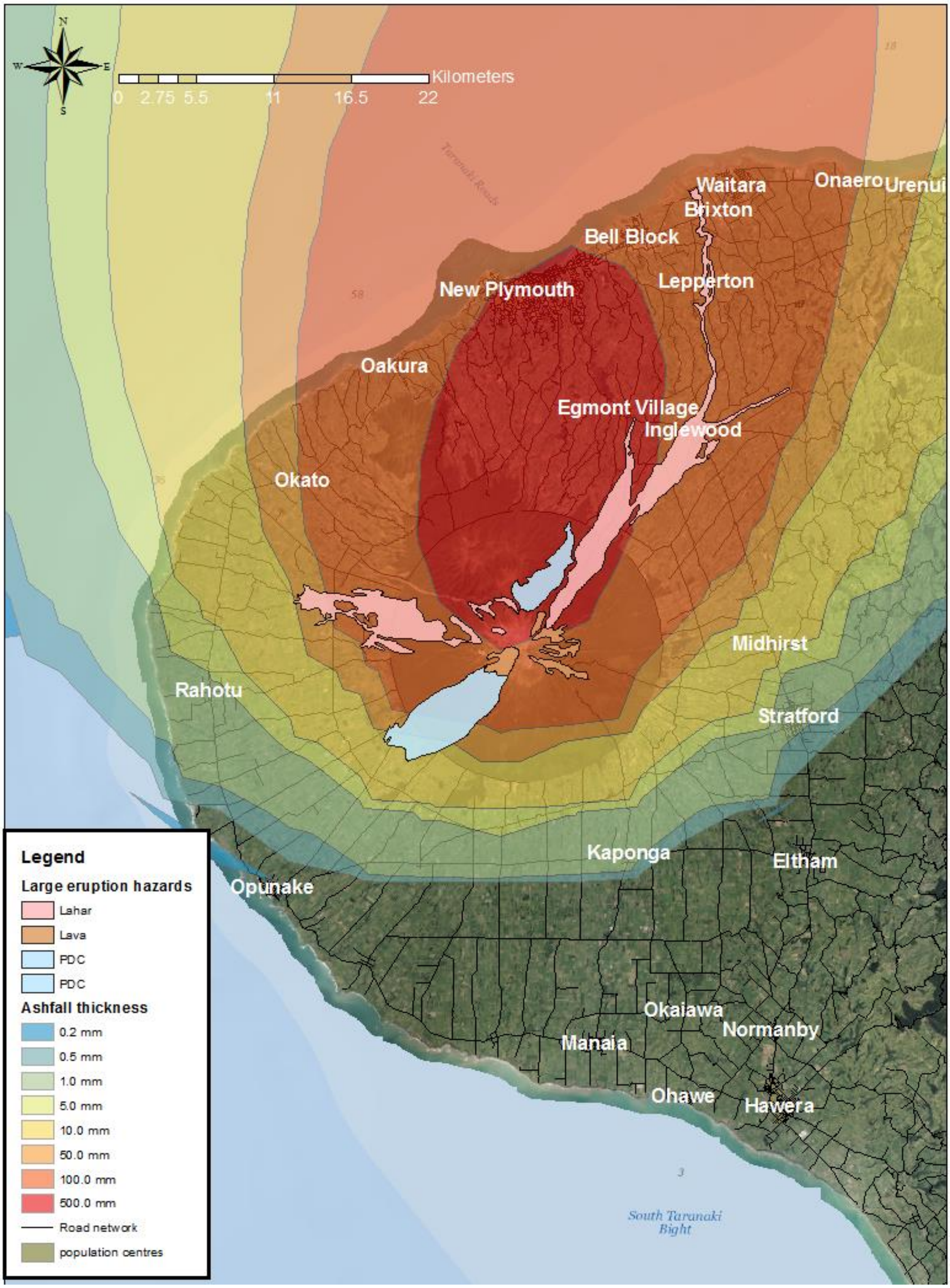

Figure 2.6 Mt. Taranaki - Large eruption scenario using hazard footprints, PDC blue, lahar red, and lava brown.

2.4 SUMMARY

The key points from the methodology development for characterising the volcanic hazards for the risk assessment framework and Mt. Taranaki Case study are summarised as follows:

- Drawing on a range of methodologies for analysing and determining the eruptive style, likely hazards and probable hazard scenarios for specific volcanoes was required to meet Objective 1. These involve literature research, review of non-academic sources, investigating studies and mapping of the geological record, and eliciting data from recent analogous eruptions.
- For the Mt. Taranaki case study, establish the scope of the study, where only hazards beyond 12-km from the summit are included. Chapter 2 identifies the primary hazards that are relevant to the petroleum sector as ashfall, PDC, Lahar and sector collapse (fulfilling Objective 2).
- Existing hazard scenarios for Mt. Taranaki have not been adequately captured with maps or GIS, leading to the development of GIS-based hazard scenarios for this thesis, based on existing geological mapping and literature research of past events. This enables an essential component of Objective 2 to be completed for later use in Chapter 5.
- Probabilistic modelling of volcanic hazards for Mt. Taranaki has yet to be developed, limiting the type of risk assessment available to be used to meet Objective 2 and later in Chapter 5.

3.0 IDENTIFICATION AND CATEGORISATION OF PETROLEUM ASSETS FOR VOLCANIC RISK ASSESSMENT

3.1 INTRODUCTION

This chapter identifies and categorises the petroleum sectors physical assets that will be exposed to volcanic hazards from future Mt. Taranaki eruptions. The chapter describes the methodology used to develop an asset inventory, details and maps how they link together into a system and categorises the functional utility of the assets (addressing Objective 2 of the thesis). The compiled asset inventory, system maps and asset categorisation directly inform the risk assessment framework in Chapters 4 and 5.

3.2 METHODOLOGY

The petroleum sector is organisationally and technically complex, as illustrated by the summary of companies involved in the Taranaki petroleum sector (Figure 1.6). The petroleum sector, like many other lifeline service providers, is described as a system of connected components, each with different vulnerabilities and exposure thresholds. To assess the likely impacts of volcanic hazards on the petroleum sector, it is necessary to:

identify bounding factors and determine the level of detail of the assessment

map the assets and how the assets interconnect as a system

map the physical asset locations

categorise the assets.

The initial step identifies any limitations and bounding factors that define the scope of work and level of detail. Published work on a variety of volcanic risk assessments uses holistic high-levels assessments through to individual components assessments of specific equipment. For holistic-high level assessments, the individual screws and seals are not identified and mapped, but rather a collection of equipment that shares the same operational task.

Secondly, the assets and system are mapped using visual diagrams. The lifecycle system maps the assets involved in the upstream petroleum sector from extraction, separation of component products and transportation and delivery systems. The assets interlink and work as a dependant petroleum system, with assets presenting a group of equipment that shares the same function. For example, all wells and their parts perform the same function to extract product from the sub-surface reservoir, and this denotes the start of the “above-ground” lifecycle of the product. A mixed methodological approach is used that includes expert judgement, literature review and site visits.

Thirdly, the systems physical asset locations are mapped. Key to the exposure assessment is building an inventory of assets using best practice methods that include the use of GIS (Remer, 2011; UNISDR, 2017). The other methods used to understand the asset locations in the petroleum sector include:

- reviewing published material
- reviewing and extrapolating existing open file datasets
- reviewing Google imagery
- reviewing Council consent information
- existing personal knowledge of locations and asset footprints

- regular industry discussions
- site visits
- expert elicitation workshop.

The asset inventory builds a spatial distribution of the petroleum assets exposed to the volcanic hazards and captures metadata to use in the risk assessment framework in Chapters 4 and 5.

Finally, petroleum assets were grouped according to their operational functionality. For example, all wells that perform the same function were grouped, irrespective of hydrocarbon type or if they are extracting or injecting. A mixed methodological approach is used that includes expert judgement, literature review and site visits.

Expert judgement is relied on for sectors with little to no prior exposure to volcanic hazards. The expert elicitation process is the most efficient and robust method to engage with experts (Evans, 2013). However, expert elicitation workshops need careful and meticulous planning to ensure identified aims and outcomes are defined and achieved and the correct attendees invited (Evans, 2013; Pattillo, 2017). The workshops' rational aims set out the desired outcomes the facilitator wishes to achieve, while the experiential aims set out what the attendees should achieve from the workshop. The petroleum sector workshop's rational aims for the exposure assessment are to derive the generic categorisation of the various petroleum assets locations in the region. The workshop's experiential aims are to:

- ensure all attendees felt their expertise was valuable to the discussions while gaining knowledge of the importance and relevance of lifeline security
- strengthen understanding and relationships between the various attendees, specifically the civil defence team and petroleum industry
- produce a favourable impression of the work, so future research, publications and collaborations are achievable
- ensure a sense of ownership in the industry of volcanic hazard risk mitigation and a desire to continue the conversation internally, sector-wide and with civil defence.

Following the workshop, all invited experts receive a summary of the workshop, feedback, and results. Thus, giving all invited experts the opportunity to contribute, and acknowledging the more introverted attendees who by their very nature require additional processing time than the workshop allows. The resulting categorisations are then used to develop the vulnerability assessment in Chapter 4.

3.3 Identification of Petroleum Systems Exposed to Volcanic Hazards in Taranaki

This study takes a high-level, generic, holistic systems approach to assess the volcanic risk to the Taranaki petroleum sector as noted in Chapter 1 and summarised in Figure 1.8. The limitations and scope are identified for the Taranaki petroleum sector, followed by mapping of the petroleum system which both informs the asset categorisation (Section 3.4).

3.3.1 Bounding factors and scope of exposure assessment

Identifying the petroleum sector systems and assets in Taranaki is a key step in defining the scope of the exposure assessment and any bounding limits. The geographic extent of the study includes all permanent petroleum extraction, production, processing, refining, transmission and storage assets in the Taranaki region. It was decided to only focus on "above-ground" physical assets and to exclude subsurface assets. This limitation was based primarily on the hazard assessment (Chapter 2) that it would be highly unlikely that any magmatic intrusions or heat-flow would directly impact the petroleum reservoirs, which typically occur at depths of 3-4 km at distances of > 13 km from the centre of Mt. Taranaki (Figure 1.5). The downstream petroleum system beyond the storage and pipe networks through to the end-users and individual homes is out of scope for this study, due to time limitations. Temporary exploration activity and equipment, such as drilling rigs are also out of scope, based on discussions with industry representatives who indicated drilling activity would not start or would conclude early and equipment shut down or securely stored, should Mt. Taranaki enter a period of unrest. Detailed assessments of asset components have not been attempted, which is better undertaken by an engineering study and would detract from the high-level holistic approach. It was also considered an unnecessary additional complexity in a Master of Science study.

3.3.2 Petroleum lifecycle systems and asset identification for the Taranaki sector.

A petroleum system map is developed that identifies and details the assets, their relationship and the flow of the system (Figure 3.1). The system was validated using expert judgment. The system follows the lifecycle of oil, gas and condensates from extraction at the wellhead, the various processes to separate the mixed product to individual product streams and then treatment to send to end users, either through pipelines or road networks. This map is generic for the industry globally, although individual sites will vary in both size and the various processes undertaken, and components required. The Taranaki petroleum sector consists of approximately thirteen separate systems working in parallel. The actual processes involved with each stage are somewhat more complicated than presented for this high-level holistic assessment of the industry. Location variability depends on the product type, volume and pressures of the reservoir, chemical composition and end use of the final product. The petroleum system involves many kilometres of pipes, separation, compression, condensing and fractionation units, valves, filters, electrical cabling, administration and control buildings, chemicals, flaring systems, and storage tanks/bullets. In addition to this, an experienced and well-trained workforce and access to road networks are required to the petroleum systems continuously. The variability between individual asset locations raised uncertainty in the risk assessment undertaken at a holistic level and captured in the uncertainties table (Table 5.2). Further asset descriptions are documented in Appendix A (7.0A1.0), derived from industry discussions and site visits.

Petroleum assets are then identified for the Taranaki sector and compiled as an asset inventory in a geospatial database. The data sources are summarised in Table 3.1, compiled from a range of open sources, with asset locations validated by using Google Earth imagery.

Table 3.1 Source data for identification of petroleum assets for the Taranaki sector.

Data Source	Usage	Data Owner	Links
Producing wells and permit metadata. Permit reports.	Metadata is used to extract details on wells that are actively producing or injecting compared to old unused wells. This site also provides permit ownership and details on asset types at locations various locations.	New Zealand Petroleum and Minerals (MBIE)	http://data.nzpam.govt.nz
Well locations	Locations of producing well sites were extrapolated to identify well site locations.	GNS Science	https://data.gns.cri.nz/pbe/
Verification	Location verification of some assets is made using satellite imagery.	Google	https://www.google.co.nz/maps/
Resource consent records.	Production facility locations and asset type information retrieved from resource consent reports.	Taranaki Regional Council	https://www.trc.govt.nz/
Asset locations and types	Asset location and details derived from discussions and site visits with individual companies.	n/a	n/a

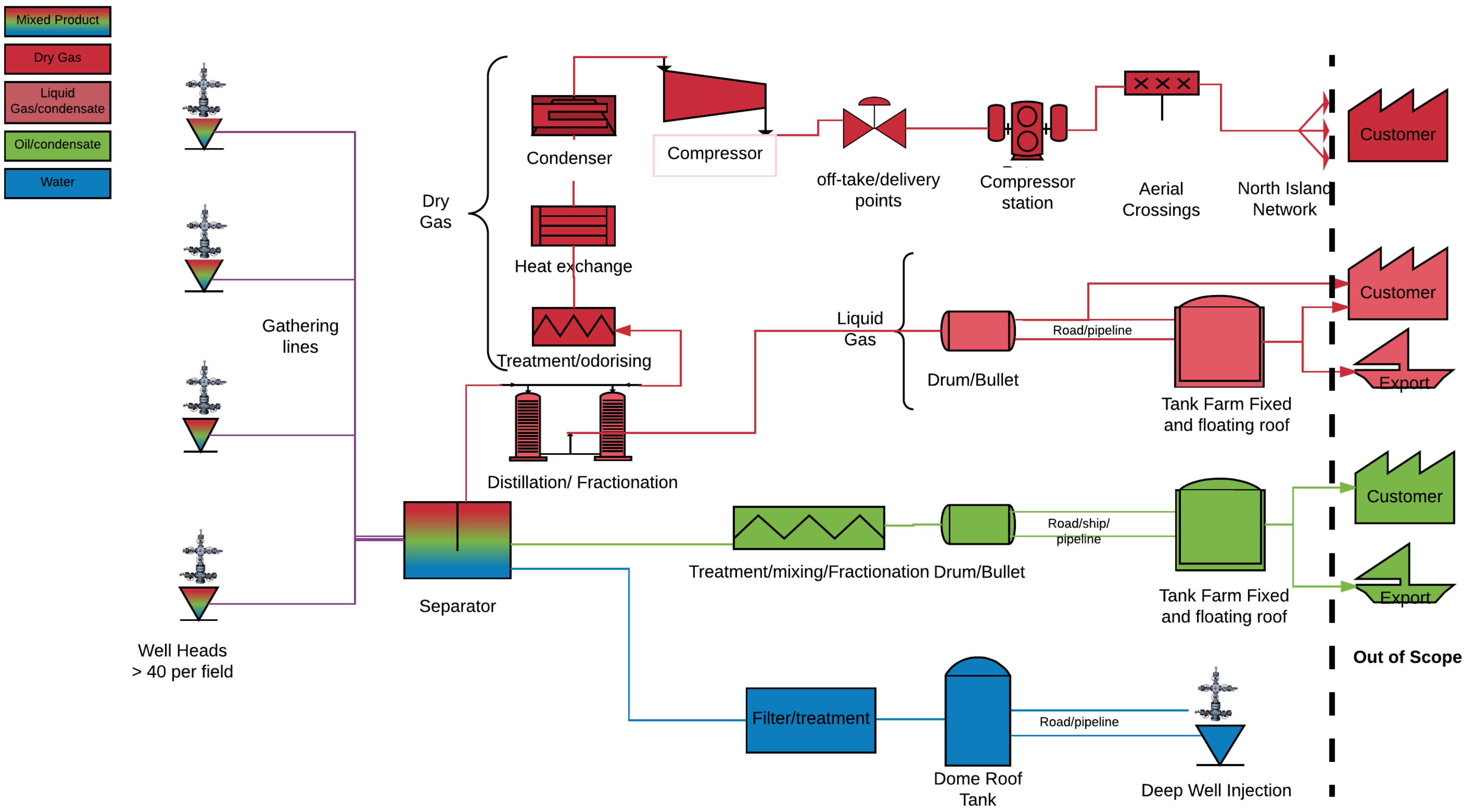

Figure 3.1 Petroleum product lifecycle.

3.4 CATEGORISATION

The primary methodological approach used to categorise the assets was an expert elicitation workshop, which was well attended, receiving high engagement from industry and excellent discussion resulting in the categorisation of petroleum assets for volcanic hazards. The detailed planning and agenda of the workshop are provided in Appendix E (7.0A5.0). The system map produced in the previous section (Figure 3.1) was used in the workshop to prompt discussion and for the proposal of asset groupings based on the function of the assets. Attendees were divided into five groups with each group having a balanced mix of backgrounds. Groups considered an initial strawman asset categorisation followed by robust discussion. The concept of grouping assets on functionality challenged many attendees who were more familiar with the classical sector view based on geographical location. Examples were used to help overcome this challenge, an example provided was that pipelines are all group together despite having varied material, burial depth, or diameter, for high-level risk assessments they can be considered to respond in the same way. Similarly, compressors irrespective of geographical location, i.e. onshore/offshore/on a production site or pipeline station, all work in the same way and therefore share a standard response to hazards at a high-level. Feedback and comments were captured and discussed in a detailed debrief meeting with co-facilitating supervisors. The expert's final asset categorisations were added to the GIS asset inventory database. The feedback was consolidated and results shared with the attendees and circulated to a broader audience of interested parties.

3.4.1 Result

Table 3.2 presents the final results of the identification and categorisation the petroleum sector assets for volcanic risk assessment. The petroleum product lifecycle is illustrated in Figure 3.2, showing the agreed asset category grouping. The inventory was then updated to reflect the various asset types at each location resulting in 247 different assets captured in the inventory, with a map showing their geographical distribution in Figure 3.3. Several sites around the Taranaki region contain multiple asset category types due to the co-location of assets for operational expediency. The building asset category is excluded from the development of vulnerability models in this thesis (Chapter 4), resulting from expert judgement and availability of existing material on volcanic assessments for the building type. Additionally, industrial users are out of scope as detailed in Section 3.3.1. The produced asset inventory and asset classification for Taranaki petroleum assets for volcanic hazards is a new contribution to risk research. The holistic level asset inventory is applicable to other hazards such as flooding or seismic risk assessments in identifying the various asset locations, although a reclassification of the asset categories may be required.

Table 3.2 Final physical asset categories for the petroleum industry for volcanic risk assessment. Photos and more detailed descriptions of asset categories are in Appendix A (7.0A1.0).

Asset Category	Number of assets recorded	Description
Wells	94	Standalone Well pad, where the well may be producing, injecting or have been either shut-in, suspended or abandoned. Some pads will have a small amount of associated equipment such as compressors, flares and may or may not have on-site staffing.
Pipelines	39	Multiple types, diameters and burial depths and content. From mixed product gathering lines to high-pressure gas lines, low-pressure lines, or water. A sub-category includes where pipelines become exposed for aerial crossings, generally over rivers, or risers where tie in points occurs as well as buried pipelines.
Production Facilities	43	These are the most complex of asset locations comprising many kilometres of pipeline, cooling and separating towers and storage as the hydrocarbon product is separated into components of water, gas, oil, condensate and prepared for transportation. They may be small satellite operations or much larger scale. They tend to comprise of multiple sub-processors, and storage tanks, flares, operation offices, water pits for fire safety and have staff continuously on-site. Depending on scale product is the put into pipelines or transported by road or maritime networks.
Storage Tanks	28	Storage tank, this grouping contains various products and comes in a wide range of construction designs, sizes. Most notable are the two sub-sets of fixed and floating roof construction types.
Buildings	35	This category includes onsite control buildings and head office buildings. Onsite buildings vary from portacabins, converted shipping containers to designed structural office buildings.
Industrial users	8	End users may be Methanol plants, LPG bottling stations, dairy processing or fertiliser factories that rely on the product.
Total number of assets	247	

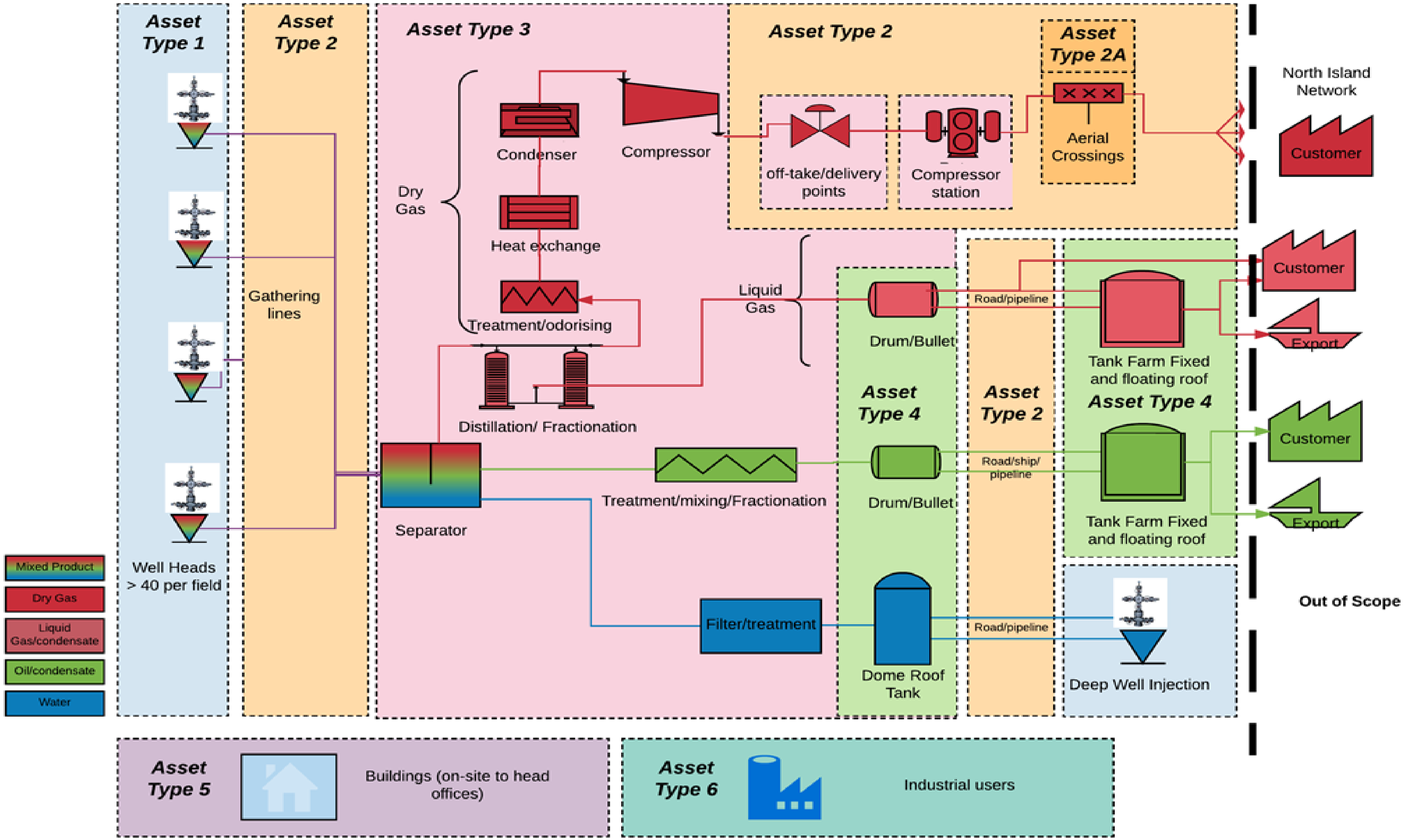

Figure 3.2 Final physical petroleum asset groupings for volcanic risk assessment.

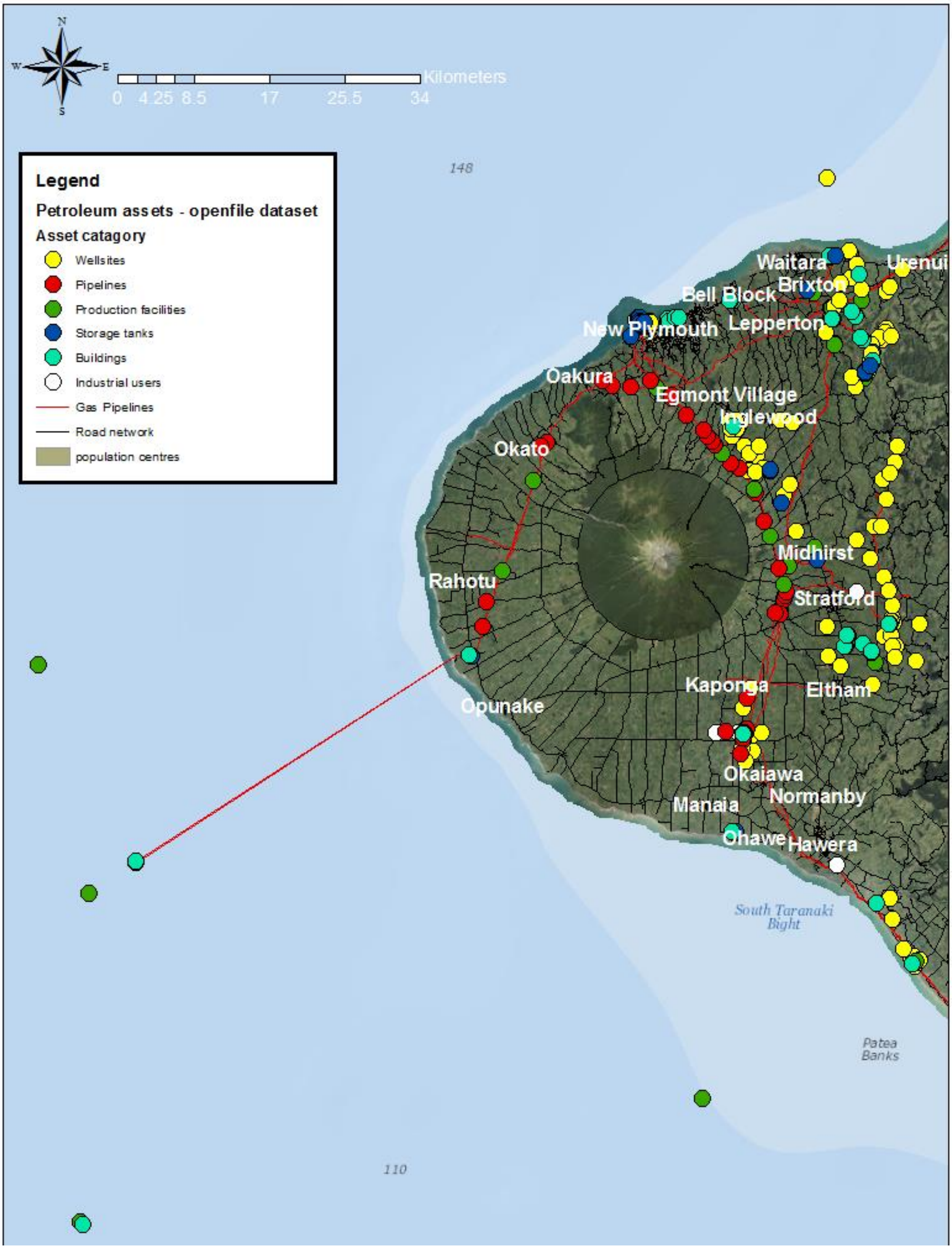

Figure 3.3 Map of the various physical petroleum assets in the Taranaki region, shown by asset type.

3.5 SUMMARY

The critical points of the methodology developed for the identification and categorisation of petroleum assets for the risk assessment framework and the Mt. Taranaki Case study can be summarised as follows:

- A mixed methodology approach was required to understand the petroleum sector that includes literature review, expert elicitation, developing industry partners and site visits and discussions with asset managers. The development of relationships with the petroleum sector of interest was essential to gain an accurate insight of the complexity and draw on expert judgement.
- The incorporation of GIS into the methodology was essential for developing an asset inventory that can then be utilised by future stakeholders, scientific studies or risk modelling using specialist software, and fulfilling Objective 1. Additionally, the risk analysis performed in Chapter 5 relies on the overlay of the GIS scenario developed in Chapter 2.
- The expert elicitation process was vital to validate the development of categorisation, especially for complex industries with wide variability and geographical locations of assets. For the Taranaki case study, the process of an expert elicitation workshop not only helped satisfy Objective 2 but had experiential outcomes for the sector that helped to meet Objective 3.
- A total of 247 physical assets are recorded for the petroleum sector in Taranaki in the asset inventory, and six asset groups identified. Only four asset categories are in scope for the remainder of the thesis: wells, pipelines, petroleum facilities and storage tanks. A holistic system approach was used for the Taranaki sector, compared with an individual component level study.

4.0 DEVELOPING VULNERABILITY MODELS FOR THE PETROLEUM SECTOR FOR VOLCANIC RISK ASSESSMENT

4.1 INTRODUCTION

This chapter presents the development of vulnerability models for the petroleum sector's physical assets, for application in a volcanic risk assessment (Chapter 5). The vulnerability assessment uses a mixed methodology approach that includes a literature review and expert elicitation, to develop theoretical vulnerability models for the petroleum sector. These vulnerability models build on the hazard and exposure assessments developed in Chapters 2 and 3, for use in the risk assessment of the Taranaki petroleum sector to volcanic hazards in Chapter 5 (fulfilling Objectives 1 and 2 of the thesis).

4.2 DEVELOPMENT OF VULNERABILITY MATRICES FOR THE PETROLEUM SECTOR FOR VOLCANIC RISK

Developing vulnerability models requires building a relationship between the impacts (damage, loss of service) from different volcanic hazards and the variable intensities (e.g. dynamic pressure for PDC, or static load for tephra fall) that occur, for each of the petroleum asset types (G. Wilson et al., 2017). Vulnerability model development is a challenging task when there are no known quantitative recorded volcanic hazard impacts (G. Wilson et al., 2014). Such is the case for petroleum sector assets where no other previously known attempts at this task has occurred. Therefore, developing a robust methodology which could be achieved within the timeframe of the thesis has been a critical step. The methodological steps to develop the vulnerability models for the petroleum assets are described in Sections 4.2.2 - 4.2.5, followed by the results and final vulnerability models presented in Section 4.3.

4.2.1 Methodology

Volcanic vulnerability assessments focused on physical vulnerability employ a range of methods that incorporate qualitative or quantitative impact data. Physical vulnerability models develop relationships between the hazard intensity and its impact on infrastructure, referred to as the impact metric, of which there are five main approaches (Figure 4.1). Impact metrics categorise the impacts into discrete states based on physical damage, function or economic loss, and associate a hazard intensity range to each category (G. Wilson et al., 2017). A conceptual model for such relationships has been developed for the volcanic risk assessment of ash and tephra impacts on buildings (Figure 4.2). Impact data can be derived from empirical, analytical, expert judgement or hybrid (mixed) methodologies, which inform both the impact metrics (IM) and hazard intensity metric (HIMs) that combine to form the vulnerability models (G. Wilson et al., 2017; G. Wilson et al., 2014).

Volcanic vulnerability assessments and models tend to be derived from post-event recognisance impact assessments, in some cases supplemented by empirical laboratory experiments for individual components (G. Wilson et al., 2017; G. Wilson et al., 2014). Examples include research done on the impacts of various volcanic hazards on building types following numerous recent eruptions (Baxter et al., 2005; Jenkins et al., 2013; Spence, Kelman, Baxter, Zuccaro, & Petrazzuoli, 2005; Spence, Zuccaro, Petrazzuoli, & Baxter, 2004; Valentine, 1998). Additionally, examples for a high-level sector-wide approach for the agriculture sector consider volcanic impacts and ashfall in depth, from a variety of past eruptions and modelled hazard scenarios (Blake et al., 2015; Craig, Wilson, Stewart, Outes, et al., 2016; Craig, Wilson, Stewart, Villarosa, et al., 2016; Wild, 2016; T. M. Wilson, Kaye, Stewart, & Cole, 2007; T. M. Wilson et al., 2013; T. M. Wilson et al., 2009).

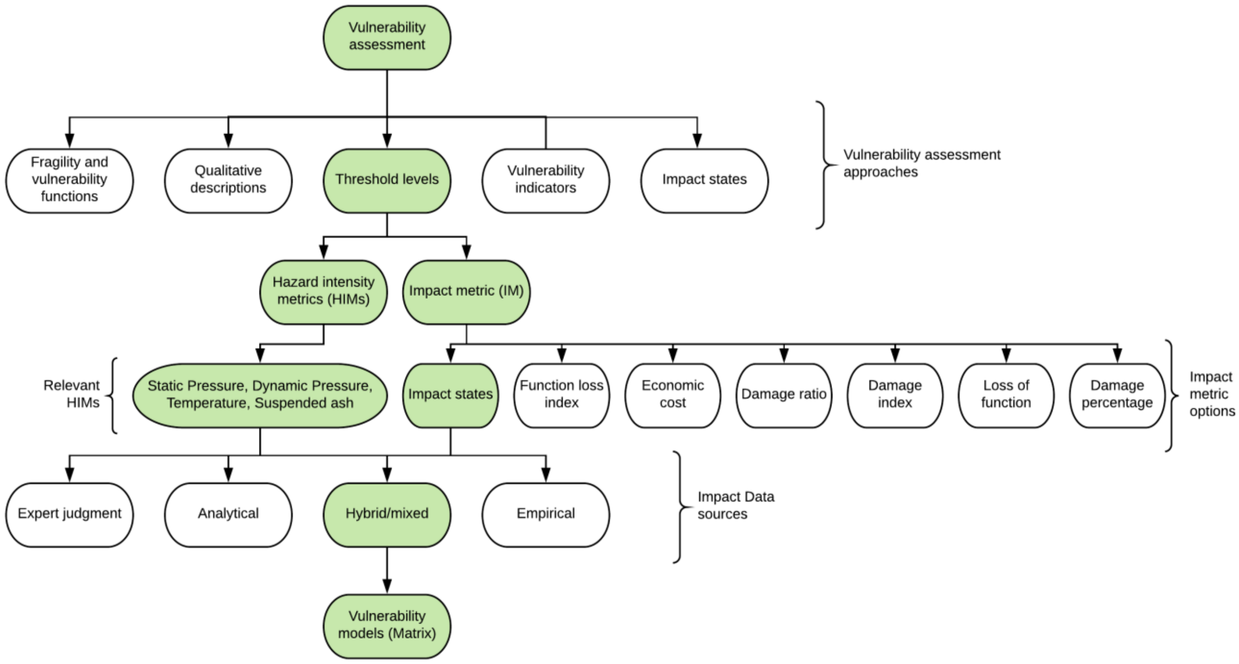

Figure 4.1 Volcanic vulnerability assessment option adapted from G. Wilson et al. (2017). Green path highlights options used in this study to develop the volcanic vulnerability assessment for the petroleum sector.

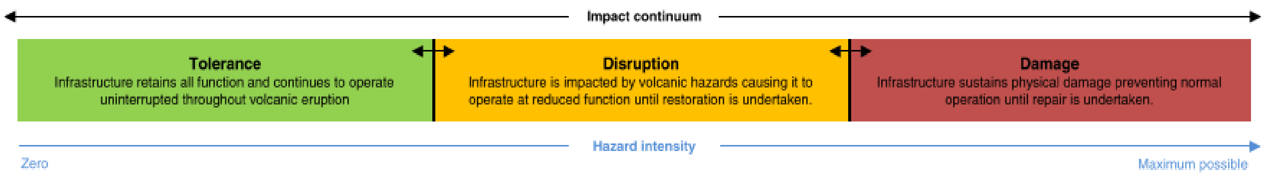

Figure 4.2 Conceptual model of the impact states for a volcanic vulnerability model of ash and tephra on buildings (G. Wilson et al., 2014).

The methodological steps developed for the vulnerability assessment of physical petroleum assets to volcanic hazard in this thesis are:

1. review of published material for existing or comparable impact data
2. review available vulnerability model designs
3. selection of most appropriate model and relevant HIMs (and terminology) to develop a template model
4. review literature for petroleum asset damage from key HIMs from all hazards
5. develop initial vulnerability matrix with examples of thresholds for key HIMs
6. run expert elicitation workshop to develop vulnerability models for all asset categories and HIMs for relevant volcanic hazards
7. compile feedback and additional literature review to produce final models
8. provide results to workshop attendees with an opportunity for additional comments.

A key part of the methodology approach has been the close engagement with the petroleum industry to inform and review the development of the vulnerability (and exposure) models. Petroleum sector engagement involved one-to-one discussions and an expert elicitation workshop, bringing petroleum industry representatives together to develop the final vulnerability models collaboratively. Four vulnerability models were developed for the Taranaki petroleum sector using this methodology, based on the asset types identified in Chapter 3. The expert elicitation workshop is discussed in Section 4.2.4, Chapter 3 and details of the agenda and attendees are provided in Appendix E (7.0A5.0). The petroleum sector workshop's rational aims for the vulnerability assessment were to:

- define the damage impact states and threshold categories
- prioritise interdependencies of the various asset categories.

The workshop's experiential aims are the same as stated in Chapter 3, Section 3.2. Following the workshop, all invited experts received a summary of the workshop, feedback, and results. This gave all invited experts the opportunity to contribute and accommodated the more introverted attendees, who by their very nature require more processing time than the workshop allowed. The hazards relevant to the petroleum vulnerability models were informed from the volcanic hazard assessment (Chapter 2), and the asset categories are requiring vulnerability models were defined in the exposure assessment (Chapter 3). The resulting four vulnerability models were then used to develop the risk assessment in Chapter 5.

4.2.2 Quantifying vulnerability of petroleum assets

The first steps in deriving vulnerability models for the Taranaki petroleum sector were to consider any known impact data from published material and determine the methodological approach to use. As previously mentioned, the only known qualitative account of volcanic impacts on the petroleum sector from international case-studies was observed at the Drift River terminal during the 1990 and 2009 Redoubt eruptions in Alaska (Bull & Buurman, 2013; Cook Inletkeeper, 2009). The challenge faced by the Taranaki petroleum sector is the lack of empirical volcanic hazard impact data, requiring a theoretical approach to derive the vulnerability models from (Figure 4.1). Additionally, any results need to align with other lifeline volcanic assessments for future interdependency studies, as well as interpretable and practical to inform future research for the Taranaki petroleum sector. Reviewing published material on the methodological approaches for vulnerability models determined that the threshold approach be the most appropriate for the Taranaki petroleum sector. The threshold approach allows for the development of a relationship between the hazard impact metrics and the theoretical thresholds at which functionality is likely to be impacted, and lends itself well to areas lacking in empirical data (G. Wilson et al., 2017; G. Wilson et al., 2014). However, this approach may not be suitable for all hazard intensity metrics for the various asset categories of this study, and alternative approaches may be required for future more detailed component level vulnerability assessments. Examples of the threshold approach include tephra, ash-fall and PDCs assessments (Craig, Wilson, Stewart, Outes, et al., 2016; Jenkins, Wilson, et al., 2014; Spence, Zuccaro, et al., 2004; G. Wilson et al., 2014). There is variation within these examples around the number of discrete impact metrics and the terminology used, which varies based on the infrastructure sector in consideration.

As empirical datasets or numerical modelling are not known to be available to inform the impact metric data for the relationship, a hybrid or mixed methodological approach was used to derive the impact data, utilising expert judgment (G. Wilson et al., 2017). The hazard intensity metric data is informed by Chapter 2. A terminology relationship was developed to address the variation between volcanic risk professionals and petroleum sector workers and overcome an anticipated terminology barrier. Providing this relationship enabled the petroleum engineers to understand the physical forces that volcanic hazards pose to the physical infrastructure. Petroleum engineers that design and work with the physical infrastructure for the petroleum sector, and related engineering design standards, use different terminology to that used by typical volcanic risk professionals. For example, petroleum engineers design for snow loading using static pressure, compared to a thickness of snow measurement (Standards New Zealand, 2003b). The HIMs and hazard relationship developed (Figure 4.3) allows the engineers to relate the relevant HIMs to measurable thresholds for the petroleum sector. This relationship is equally relevant for other lifeline infrastructure studies involving engagement with engineering professionals.

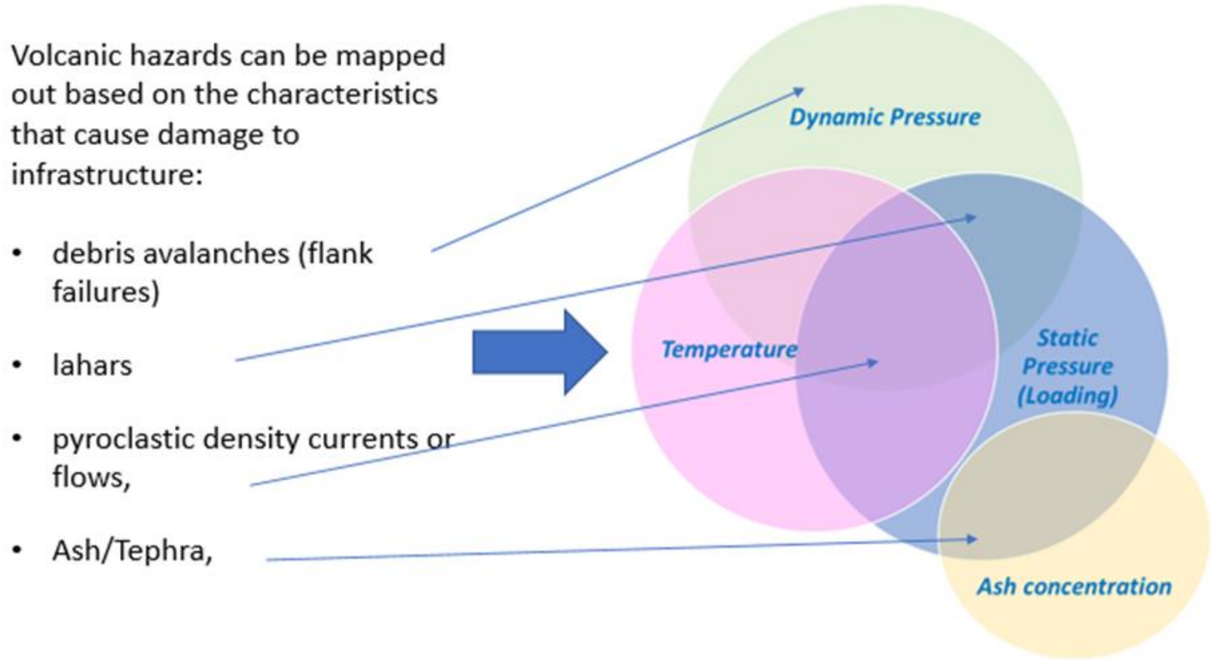

Figure 4.3 Relationship between revised HIMs (right) and volcanic hazards (left).

Returning to the development of the impact metric data for this thesis, a variety of options are available in published material (Figure 4.1). The impact state option was selected after comparison of these options, existing impact data, and the thesis aim to consider functionality based on hazard impact. The impact state option allows discrete categories with hazard intensity thresholds that define changes in functionality from tolerance, to disruption, to damage (G. Wilson et al., 2014). The impact state option works well for the theoretical approach required for the petroleum sector, where multiple volcanic hazards are considered (Chapter 2). Additionally, the use of impact states is common in published work on volcanic vulnerability assessments of critical infrastructure, allowing for comparison with the results from this thesis. For this thesis, a four-level impact state model was developed for the Taranaki petroleum sector, based on the conceptual model for impact states (Figure 4.2). By comparison, other studies have used a greater number of impact states. Jenkins et al. (2014) proposed the consistent use of six descriptive states or levels (D0-D5), with varying function descriptions based on the infrastructure type. Thus, enabling easier comparison between the various infrastructures when considering a regional overview, or multiple hazards. RiskScape, a New Zealand developed software designed for estimating asset impacts and losses from single or multiple natural hazards, also uses a six-level damage state (D0-D5) (GNS Science & NIWA, n.d.; RiskScape Damage State Working Group, 2016). The use of six states was found to be too complicated for this preliminary research, where the theoretical nature of this research makes it difficult to determine the delicate details and differentiate the likely impacts. Therefore, a simpler four state scale was adopted for the Taranaki petroleum sector (Table 4.1). Some consistency is maintained with the Jenkins et al. six-level scale, as this study simply omitted the moderate (D2) and severe (D4) states. Additionally, impact damage is binary for some hazards. For example, sector collapses create massive debris avalanches and will likely destroy any exposed assets. In these cases, the four-scale model is adapted by omitting the intermediate steps, leaving a two-level scale. By adopting this structured approach, the four-level impact state model derived for the Taranaki petroleum sector provides an opportunity for refinement in future research, as asset threshold ranges are analysed in detail.

Table 4.1 Four-level impact state model for the vulnerability models of petroleum assets in respect to volcanic hazards. Colours are aligned to the conceptual model presented in G. Wilson et al. (2014) (Figure 4.2).

D0	No physical damage
D1	Minor (no structural) damage
D2	Major (Structural) damage
D3	Total physical asset destruction, i.e. catastrophic failure (requires full replacement rather than repair).

4.2.3 Literature review

The next steps in developing volcanic vulnerability models for the Taranaki petroleum sector was to review published material for comparable impact data that can inform the theoretical approach and expert elicitation workshop (Section 4.2.4). Here, the damage or impact thresholds and states captured for analogous events, hazards and asset types are reviewed to extract provisional thresholds to assign to the four-level impact model for the Taranaki petroleum sector. The four main asset types, identified in Chapter 3, for the focus of the literature research are:

- wells
- production facilities
- pipelines
- storage tanks

There is a void of literature and case-studies of where petroleum infrastructure and volcanic hazards have interacted internationally, except for one example of the Drift River Oil Terminal, Alaska. Lahars and flooding directly impacted the downstream petroleum sector at the Drift River Oil Terminal during both the 1990 and 2009 eruptions of Redoubt Volcano, Alaska (Brantley, 1990; Dorava & Meyer, 1994; Waythomas, Pierson, Major, & Scott, 2013). Numerous flood and lahars breached existing mitigation levees and dykes during both eruptions, causing evacuations and the facility to shut down (Brantley, 1990; Dorava & Meyer, 1994). While the terminal was not an active production or exploration location, the indirect impacts of the eruptions resulted in the suspension of offshore production from platforms that supplied oil to the terminal (Brantley, 1990). Additionally, the floods and lahars also exposed the underground pipelines (Dorava & Meyer, 1994).

Following the 1990 eruptions, Drift River Oil Terminal improved their risk mitigation by building dykes and levees around the facility to reduce direct impacts from lahars, floods and channel erosion (Waythomas, Dorava, Miller, Neal, & McGimsey, 1997). However, during the 2009 eruption, the dykes were still breached, and although the debris did not reach the oil storage tanks, it did trigger an emergency evacuation (Bull & Buurman, 2013; Waythomas et al., 2013). The debris inundated the facility’s runway, preventing any emergency response to an oil spill, which raised concern among the local communities and led to the removal of 6 million gallons of oil stored at the facility (Bull & Buurman, 2013; Cook Inletkeeper, 2009). This example highlights some of the risks from lahars and flooding associated with volcanic eruptions to the petroleum industry. A primary contributing factor to the high flood levels from Redoubt Volcano was the glacial meltwaters derived from the heat flow of the lahars, lava and pyroclastic flows (Waythomas et al., 1997). Although Mt. Taranaki does not have glaciers, it does have substantial snow caps throughout most of the year, that require consideration when modelling flood levels in addition to the regions higher than average rainfall. The rainfall in the region has proven to contribute to a heightening likelihood of remobilised debris and lahars (Johnston et al., 2011; Neall, 2011).

Aside from the Drift River example, the lack of documented volcanic impacts on the petroleum sector led to a focus on the literature review to consider similar structures and hazards. Additionally, observations and research into tsunami washout and scouring impacts can be drawn on to give insight into the lahar and PDC dynamic pressure and erosion characteristics. For example, the observed gas pipelines and storage tank damage following the 2015 Chile Tsunami provided insights into how the sector could improve resiliency (Horspool, Cousins, & Power, 2015). Findings from the extensive literature review undertaken are summarised in Table 4.2. The buildings asset category is excluded from the scope of this thesis (Chapter 3). However, acknowledgement of current volcanic hazard exposure research, including that of buildings, informs the literature review for other asset types. Residential building studies of tephra and ash fall loading completed in recent years highlights examples of observed damage (Baxter et al., 2005; Jenkins et al., 2013; Jenkins, Spence, et al., 2014; Spence, Kelman, Baxter, et al., 2005; Spence, Kelman, Calogero, et al., 2005; Spence, Zuccaro, et al., 2004; Valentine, 1998; Zuccaro, Cacace, Spence, & Baxter, 2008). Furthermore, where existing building compliance contains snow loading engineering, these can be drawn on to give preliminary threshold ranges (Standards Australia & Standards New Zealand, 2009a).

Table 4.2 Summary of the literature review into vulnerability thresholds from similar events and hazards.

HIMs	Example assets	Analogous hazards, asset types, or constraints	Examples of analogous events or considerations	Provisional thresholds	References
Static Pressure	Storage tanks - floating roof designs	Similar hazards, rainfall changes to ash density qualities. Other sectors pipelines	Laboratory studies, Snow loading designs Rainfall and ash Industry standards	< 1 kPa 1-1.25 kPa 1.25 – 2 kPa > 2 kPa	(American Petroleum Institute, 2013; Efford, Clarkson, & Bylsma, 2014; Gehl, Quinet, Le Cozannet, Kouokam, & Thierry, 2013; Macedonio, Costa, & Folch, 2008; Milazzo et al., 2013; Milazzo et al., 2012; Neall, 2011; Standards New Zealand, 2003b)
Temperature	Pipelines - aerial crossings	PDC impacts on similar plastics, Operational working temperatures Other sectors pipelines	Merapi eruption, 2010 Montserrat eruption, 1995 - present Mt. Redoubt 1991, 2009 Volcan de Colima, 2015 Mt. St. Helens 1980	< 45 ˚C 45-55 ˚C 55-500 ˚C > 500 ˚C	(Arguden & Rodolfo, 1990; Australian Energy Market Operator Limited, 2014; Bredero Shaw, n.d.; Fletcher & Nicholas, 2014; Jenkins et al., 2013; JFE Steel Corporation, n.d.; Mullineaux & Crandell, 1962; Nolan, 2014; Shaw Pipe, 2010; Voight & Davis, 2000)
Dynamic Pressures	Pipeline - aerial crossing	Extreme weather, Tsunamis, Explosives Other sectors pipelines Scouring - tsunamis or lahars PDCs – fringe effects and central zones	Great Japan Earthquake & tsunami 2011, Chile tsunami 2015 Gulf war 1991, Eruptions as above Modelling and laboratory studies Maui Pipeline failure 2011	< 0.5 kPa 0.5-1 kPa 1-2 kPa > 2 kPa	(American Society of Civil & Wind-Induced Forces Task, 2011; Baek, Kim, Kim, Koo, & Seok, 2012; Baxter et al., 2005; Belousov, Voight, & Belousova, 2007; Dorava & Meyer, 1994; Jenkins et al., 2013; Meyer et al., 2013; Ministry of Business, 2012; Pilcher & Sexton, 1993; Ramasamy, Hill, Hepper, Bull, & Clasper, 2009; Spence, Baxter, & Zuccaro, 2004; Spence, Zuccaro, et al., 2004; Vector Gas Limited, 2012)
Suspended Ash	Compressors (air intake equipment)	Dust storms Aircraft engines	Other eruptions as above Calbuco Volcano, 2015	< 0.5 gm^3 0.5-1.5 gm^3 1.5 - 2 gm^3 > 2 gm^3	(Bebbington, Cronin, Chapman, & Turner, 2008; Bonadonna & Houghton, 2005; Chapman et al., 2007; Hayes, Wilson, Deligne, Cole, & Hughes, 2017; Hayes, Wilson, & Magill, 2015; Houghton et al., 2006; Jenkins, Wilson, et al., 2014; Johnston et al., 2004; Stewart et al., 2006; Williams & Wilson, 2017; T. M. Wilson & Kaye, 2007; T. M. Wilson et al., 2009; T. M. Wilson et al., 2012; T. M. Wilson et al., 2014)

4.2.4 Expert elicitation

4.2.4.1 Overview of the workshop planning and execution

An objective of the thesis was to engage with the petroleum industry to raise awareness and share knowledge of volcanic hazards (Objective 3). Additionally, discussion and consultation with the petroleum industry validated the application of the framework and derived results (Objective 2). An iterative approach was used to engage with a small group of core companies and develop partnerships. Initial contact was made through existing industrial relationships and aided by Petroleum Exploration & Production Association of New Zealand (PEPANZ). Non-disclosure agreements were drafted to mitigate confidentiality risks. Initial discussions were undertaken in company offices (New Plymouth) and involved a combination of office-based discussions and site visits with ongoing discussion during the site visits. Follow up email correspondence provided clarifications and answers to further questions. These companies agreed to collaborate by sharing data, information and organising site visits in addition to attending the expert elicitation workshop. Geospatial data derived from the research was also shared with some companies to validate site locations and functions (Chapter 3).

A more extensive group of industry representatives, regulators, civil defence and local and regional council staff from the New Zealand petroleum sector, along with members of the volcanic impact science community were invited to an expert elicitation workshop, seven months into the twelve-month thesis timeframe. The workshop's facilitation was accomplished in conjunction with two members of the supervisory team and presented a personal development aspect to the research project. The workshop's rational aims for the Taranaki petroleum sector for the development of vulnerability models to volcanic hazards were to:

- define the damage impact states and threshold categories
- prioritise interdependencies of the various asset categories.

The workshop's experiential aims were as previously stated in Chapter 3, which reiterating are to:

- ensure all attendees felt their expertise was valuable to the discussions while gaining knowledge of the importance and relevance of lifeline security
- strengthen understanding and relationships between the various attendees, specifically the civil defence team and industry
- produce a favourable impression of the work, so future research, publications and collaborations are achievable
- ensure a sense of ownership in the industry of volcanic hazard risk mitigation and desire to continue the conversation internally, sector-wide and with civil defence.

The workshop was held in Stratford and hosted by the Regional Council. Attendees received the provisional vulnerability model template and asset categorisations ahead of time, derived in previous sections, which helped them understand the tasks required of them and created a focus for discussion. Additionally, the facilitated discussion and structuring of the workshop allowed separate sessions to test and discuss the issues and challenges with developing the theoretical vulnerability models for each asset, and to capture feedback. Appendix E (7.0A5.0) provides a more detailed account of the workshop.

4.2.4.2 Summary of volcanic hazard impacts to petroleum assets - discussions from the expert elicitation workshop

In this section, the key discussions and points raised by the attendees during the expert elicitation workshop are grouped by hazard type and summarised. Potential consequences of volcanic hazard impacts highlighted by the petroleum sector experts through the discussions provided direction for further work.

Ashfall hazards were a critical concern through static loading, particularly for buildings and floating roof storage tanks. Static pressure and suspended ash concentration were not perceived as a concern for pipeline and well assets due to the spherical shape of pipelines, the small surface area of wells, and lack of moving parts. The expert group raised concern over how such storage tanks would cope with ash fall and ash loading, with specific concerns raised around cleaning. Floating roof tanks were identified as being difficult to clean under normal circumstances, relying on rainwater drainage channels. The experts felt repeated ash fall events would be problematic, especially if the ash became wet. One expert noted that if certain construction types of floating roof do not receive annual inspections, reduction in performance levels occurs that will negatively impact the load baring thresholds. Upon reflection, the current level of inspection may not be sufficient in New Zealand. Various locations at risk from volcanic ashfall use floating roof storage tanks for refined oil products. For example, floating roof storage tanks are used in Auckland to store aviation fuel. This research established that more detailed studies need to be undertaken to evaluate static pressure risk from volcanic hazards. It was found that current regulations for building designs do not consider volcanic hazards. Therefore, further studies are required to investigate if elevating standards for structures in volcanic hazard zones is an appropriate method to improve ash loading resilience. Potential changes to design standards is an area that warrants further research to influence building standards the upstream petroleum sector of New Zealand and globally.

The temperature HIM proved to be an interesting discussion topic, with experts surmising that gaskets and seals would be vulnerable to temperatures above 80 ˚C. The experts found it challenging to determine exact threshold values for the point at which seals would be damaged compared to destroyed. Suggesting future laboratory research may provide such results. The experts did note the consequences of gasket and seal failure is critical, requiring them to be replaced even with slight damage. Precise inspections of all equipment are required to determine damage, which takes a longer time, causing potential delays in restarting production. The timeframes from damage to failure are critical and at this point unknown, requiring further research. This concern was a key take-home point for many of the attendees that they had not considered before the workshop. Additionally, the temperature ranges proposed by the expert panel were different to literature review findings, especially for pipelines, validating the use of expert opinion for such complex industries. In-depth discussion around the duration of exposure occurred in the workshop with experts concluding that exposure to high temperatures is likely to be short when associated with fringe PDCs or lahars, compared to lava or core zone of PDCs, but still potentially significant.

The dynamic pressures that wellheads are built to withstand, based on internal pressure design standards, were found to far exceed dynamic pressures expected from volcanic hazards. Extreme dynamic pressures were observed in the Gulf War, where explosive blasting of the control valves on the “Christmas tree” or “well stacks” were used to release oil flows which were ignited, reaching temperatures of over 1100 ˚C. Therefore, if internal design pressures are a good analogue for external pressure thresholds, wellhead structures are resilient to the volcanic hazards they may encounter. However, the well-stacks and control valve units may not be as resilient. For storage tanks and pipelines, the experts determined that dynamic pressures from hyper-concentrated lahars would be the most damaging hazard, due to the scouring effects of some lahars. The expert's lack of knowledge around lahar and PDC variations was identified as a constraint on the process, which can be addressed in future research. However, the discussion remained robust, identifying critical variables that would influence the impacts, such as exposure duration, length of span and alignment to be addressed in future research. Additionally, experts identified that floating roof storage tanks designs require a dyke and levee system or bund surrounding them. The experts raised concern that while this can offer protection, lahar debris may be elevated by the structures and puncture tanks. Therefore, finding that the assumption dyke and levees provide complete protection is an unsafe one.

The experts concluded that for the production facilities asset type, any damage from static pressure and laharic dynamic pressure would be considerable, thus bypassing the minor damage state. For the lahars, the expert's knowledge deficiency, mentioned previously, constrained discussions during the workshop, leading to some uncertainty. This uncertainty manifested in the matrix through assumptions made on intensity and exposure duration of lahar and other volcanic hazards. The PDC damage review provided thought-provoking findings, where wind loading for flare stacks was identified as an example of vulnerability. Wind speed designs consider the speed at which damage is caused by resonance. Links between PDC dynamic pressure and wind speed design were identified for further research.

Ash concentration was identified as a critical risk to the production facilities asset type, as many components have moving turbines or fans and rely on good quality air. Experts concluded that small amounts, particularly the finer ash, would cause damage by blocking filters leading to overheating. Some assets use turbines, like aeroplane engines, which have extensive research into the impacts of ash. Therefore, inferring from existing studies, consequences of direct abrasion of turbines from abrasive ash would cause significant damage. However, experts highlighted that the damage would likely require parts to be replaced rather than the destruction of the asset unless the damage caused secondary hazards such as a fire. Experts also identified the ash as a concern for water supplies, that the petroleum sector requires for fire safety. The ash can cause operational issues or damage to water pumps as highlighted in existing volcanic hazard impact research. However, one expert identified that the seal quality on the tanks would also be compromised by the abrasion and corrosion properties of the ash. They expanded on this, suggesting damage of this type is gradual where replacement is required within 6-12 months depending on the level of damage. This collaborated the findings from the temperature discussions, that small seals and gaskets, while relatively minor components are widespread across many asset categories. They are expensive to replace and difficult to monitor the gradual damage or shorten lifespan, providing an opportunity for future research to aid the petroleum sectors resilience and recovery.

4.2.5 Development of the final vulnerability models for the petroleum sector in Taranaki

The final stages of developing the vulnerability models were to compile the workshop feedback and provide results to the invited experts for comment. A debrief with co-facilitators and supervisors immediately followed the workshop and was essential for capturing key points. Discussion and comments from attendees captured during the workshop provided a focus for additional literature reviews and revisions to the vulnerability models. A summary report was then distributed to all participants, with a request for feedback on the developed vulnerability models. The next four sections summarise the feedback received during the final steps in developing the four vulnerability models for the Taranaki petroleum sector, followed by the final vulnerability model results presented in Section 4.3.

4.2.5.1 Asset benchmarking – expert elicitation discussion and feedback

Theoretical vulnerability models used the most vulnerable equipment example as a benchmark for each asset group, to overcome variations in the equipment between sites and within asset groups. Experts and site visits confirmed the variation in asset equipment throughout the Taranaki region for the petroleum sector. For example, building variations include shipping containers, portacabins, and structurally reinforced office buildings. This variation caused uncertainties in the generic threshold range used during the high-level vulnerability assessment. Experts identified examples of vulnerable equipment for each asset group and used these to determine the generic threshold ranges for the impact states across all hazards. For example, storage tank construction variation plays a significant factor in the vulnerability assessment. The experts confirmed that annular pontoon floating roof constructions as being the most vulnerable, especially if the pontoons are leaking and compromised already (Myers, 2017).

4.2.5.2 Static pressure – expert elicitation discussion and feedback

The expert group confirmed that snow loading standards are a good analogue for static pressure and provide maximum design loads. However, the New Zealand Standards only give prescriptive coefficients and geographical variations for alpine and sub-alpine conditions (Standards New Zealand, 2003b). This information will be more critical for detailed site-specific work and did not provide a range of probable values for the generic high-level vulnerability models. Instead, the American Petroleum Institute (API Standard 650) provided threshold values for snow loading limit designs for welded oil storage tanks (American Petroleum Institute, 2013).

4.2.5.3 Dynamic Pressure – expert elicitation discussion and feedback

The feedback from the group was clear that dynamic forces of lahars and PDC need separating, as PDCs represent a more uniform force, while lahars are more height restricted. They considered PDC dynamic force to be more uniform and analogous to wind loading, while laharic dynamic forces were felt to be more focused and unbalanced with the potential for hyper-concentrated lahars impacting the base of structures only.

The expert group referenced wind load standards set out under AS/NZS 1170 for many of the various categories, as this presented an analogous extreme dynamic force for PDCs. Wind loading as a design standard is used in the American Petroleum Institute (API) Standards, from which threshold values are inferred. Additional references have been found from other industry resource material to revise the dynamic pressures for the various asset types. For more complex asset types, such as the production facility, the expert group used flare stacks, as a vulnerable example to wind loading. Flare stack design thresholds helped to constrain the impact metric thresholds for uniform dynamic forces associated with PDCs. Examples of extreme wind damage to storage tanks in the downstream petroleum sector are Hurricane Celia (1970), Hurricane Hugo (1989), and Hurricanes Rita and Katrina (2005) also informed threshold ranges (American Society of Civil & Wind-Induced Forces Task, 2011).

For lahars, a lack of knowledge led to perceptions of the hazard coming from a video shown during the workshop and imparted by the co-facilitating supervisor's experience. The example provided showed a hyper-concentrated lahar from Curah Lengkong river in Indonesia, which had a lahar front-loaded with large boulders and debris (Lavigne, 2002). Given time constraints and understanding of the ranges of lahars, the group did not consider the more uniform sediment lahars. However, experts raised concern that storage tanks of specific designs (i.e. floating roof), tend to have dyke and levee systems or bunds surrounding them. While this will offer some protection from hazards, discussion considered that it might elevate debris carried by the lahar and puncture the tanks. The Drift River Terminal concrete dyke and levee system constructed following the 1991 Mt. Redoubt eruption offered only limited protection in the 2009 eruption (Cook Inletkeeper, 2009). If these dyke and levee systems become exposed to substantial and repeated lahars, then the protection they offer would undoubtedly be compromised. Therefore, any assumption that the dyke and levee systems provide complete protection is an unsafe one. It is also worth noting that dykes and levee systems do not surround most bullet-style, fixed roof, or open water storage tanks. Additionally, the erosional qualities of lahars were identified as a key concern in exposing buried pipelines and undermining supportive structures, and further study of these impacts was highlighted to understand the risks to petroleum infrastructure. Particular concern was raised that buried pipelines will become exposed and damaged by lahars, as at the Drift River Oil Terminal.

4.2.5.4 Temperature – expert elicitation discussion and feedback

The expert elicitation workshop produced different ranges of temperatures for the thresholds compared to the provisional ranges provided. The experts focused on the seals, gaskets and other consumable components that are vulnerable to damage. These ranges were consistent across most asset types, with 60-80 ˚C identified as the threshold at which “minor” damage would occur with “major” damage/possible destruction at 150˚C and in some cases destruction occurring above 450 ˚C. Discussion occurred around the variability in the duration of exposure to temperatures, which was perceived to be short for volcanic hazards. They perceived that dynamic forces would cause considerably more damage to assets than short high-temperature exposure, but didn’t discount the damage that high temperatures would cause.

4.2.5.5 Ash concentration – expert elicitation discussion and feedback

Expert attendees raised dust storms as a comparable analogue to ash fall, based on experiences of dust storms in the Middle-East. Petroleum sector experiences of dust storms highlight vulnerabilities and reliance on workforce and consumables to maintain assets, leading to a pre-emptive shut down for the duration of the storm during inhospitable conditions. Co-facilitating supervisors highlighted that volcanic ash would be of a much higher concentration and have more abrasive qualities than dust storms, thus likely to cause more damage. Research has found similarities between dust storms, volcanic ash hurricanes and PDCs such as high mobility rates, with differences such as the particles size, density, temperature, run-out dynamics, and concentration (Doronzo, Martí, Dellino, Giordano, & Sulpizio, 2016). From an initial response planning perspective, the mitigation actions required would be similar, in that consumables and workforce are required dependencies. The current plan by the Taranaki industry involves a short-term shut-down of all equipment and production during an eruption, to facilitate a recovery period as rapid as feasibly possible and to restart production. However, the combination of a hefty ash dose, temperature and dynamic force would likely cause damage to wires, gaskets, and seals as well as filters as a minimum. Severe damage would likely require a minimum 12-month recovery period. However, as this research is still theoretical and will remain untested until a future volcanic eruption impacts the petroleum sector or laboratory experiments occur. An additional note of caution is that remobilisation of volcanic ash can cause damage to sensitive components and care will need to be taken to mitigate ongoing risks following an eruption.

4.3 RESULTS

Using the literature search results and incorporating comments and feedback from the expert elicitation process discussed in the previous sections, final vulnerability models have been produced for the four petroleum asset categories (wells, pipelines, production facilities and storage tanks) (Tables 4.3 to 4.6).

The results highlight that:

- Wells are likely the most resilient asset type. However, associated well stacks are less resilient due to valves and in some cases electrical wiring or associated air compressor units.
- Pipelines are most vulnerable when exposed for aerial river crossings, and the erosional qualities of the lahar hazards are the most damaging for this asset type.
- Production facility assets encompass a wide range of equipment, for the dynamic pressure the flare stacks, and for suspended ash, any air intake equipment, are examples of vulnerabilities.
- The storage tank assets also encompass a wide range of designs, with floating roof designs perceived to be the most vulnerable to static and dynamic pressure HIMs.
- Wiring and gaskets, while small components of many equipment types within numerous asset categories are examples of vulnerable components. These are vulnerable to both temperature and suspended ash, with implications for recovery timeframes.

4.4 SUMMARY

The key points from the methodology for developing vulnerability models for the petroleum sector for volcanic risk assessment and the Mt. Taranaki Case study are as follows:

- The methodology includes a combination of literature review, an expert elicitation workshop and follows up with industry partners to develop vulnerability models for each asset category using a threshold level approach of a volcanic vulnerability assessment (fulfilling Objectives 1 and 2).
- Developing vulnerability matrices for complex petroleum systems at a holistic level can be simplified, by considering examples of vulnerable equipment, to benchmark damage thresholds. This approach acknowledges that such complex systems are only as vulnerable as the weakest part or component, forming the methodological approach for the development of theoretical vulnerability models as part of Objective 1.
- Lahars and ashfall (both static pressure and ash concentration) are perceived to be the primary hazards that are likely to cause the most impact on the four physical assets of the petroleum system in Taranaki. These two hazards will be the focus for impacts to petroleum assets in the Taranaki Region as the risk analysis is concluded in Chapter 5 (fulfilling Objective 2).

Table 4.3 Vulnerability model for the Well asset category (noting the resilience of this category). Mpa – MegaPascals.

Wells					
		D0	D1	D2	D3
Hazard Type		No Damage	Minor Damage	Major Damage	Destroyed
burial thickness/structural loading weights/static pressure	impact/ damage	n/a			
	Thresholds	n/a			
Temperature	impact/ damage	resilience maintained	seals/gaskets damaged	seals/gaskets destroyed	
	Thresholds	0-80 ˚C	80 - 121 ˚C	121 - 450 ˚C	> 1000 ˚C
Laharic dynamic/flow pressure	impact/ damage	resilience maintained	n/a	depends on wellhead design standards	depends on wellhead design standards
	Thresholds	0-13 MPa	n/a	13-34 MPa	>34 MPa
PDC dynamic/flow pressure	impact/ damage	resilience maintained	n/a	depends on wellhead design standards	depends on wellhead design standards
	Thresholds	0-13 MPa	n/a	13-34 MPa	>34 MPa
Suspended Ash	impact/ damage	n/a			
	Thresholds	n/a			

Table 4.4 Vulnerability model for the pipeline asset category (shading highlights lahars as the most damaging hazard impacts for this asset). kPa – Kilo Pascals

Pipelines (including aerial crossings and pipelines buried to a maximum depth of 700 mm)					
		D0	D1	D2	D3
Hazard Type		No Damage	Minor Damage	Major Damage	Destroyed
burial thickness/structural loading weights/static pressure	impact/ damage	n/a			
	Thresholds	n/a			
Temperature	impact/ damage	normal operational temperatures	Coating damage, sealing, gasket failures	loss of strength of steel	
	Thresholds	< 150 ˚C	150 - 450 ˚C	450 - 600 ˚C	>600 ˚C
Laharic dynamic/flow - variable pressure	impact/ damage	resilience maintained	depends on exposure & type of lahar		catastrophic failure, i.e. pipeline/struts destroyed
	Thresholds	0-0.05 kPa	0.05-1 kPa		>1 kPa
PDC dynamic/flow - uniform pressure	impact/ damage	resilience maintained	Minor Damage	Major Damage	catastrophic failure i.e. pipeline/struts destroyed
	Thresholds	0-0.05 kPa	0.05-1 kPa	1 - 2 kPa	>2 kPa
Suspended Ash	impact/ damage	n/a			
	Thresholds	n/a			

Table 4.5 Vulnerability model for the production facility asset category (shading highlights static pressure, lahar and suspended ash as most damaging hazard impacts for this asset). Psf- pounds per square foot, gm^3 – grams per cubic meter.

Production Facilities (excluding buildings)					
		D0	D1	D2	D3
Hazard Type		No Damage	Minor Damage	Major Damage	Destroyed
burial thickness/structural loading weights/static pressure	impact/ damage	resilience maintained	n/a	maximum load standard	Destroyed
	Thresholds	0-1.2 kPa (0-25 psf)	n/a	1.12 kPa (25 psf)	> 1.2 kPa (>25 psf)
Temperature	impact/ damage	resilience maintained	seals/gaskets damaged	seals/gaskets destroyed	
	Thresholds	0-80 ˚C	80 - 121 ˚C	121 - 150 ˚C	> 150 ˚C
Laharic dynamic/flow pressure	impact/ damage	resilience maintained	n/a	depends on exposure & type of lahar	catastrophic failure i.e. assets crumple
	Thresholds	0-0.05 kPa	n/a	0.05-1 kPa	>1 kPa
PDC dynamic/flow pressure	impact/ damage	resilience maintained	Flare stack resonance reached, or wind speed high enough damage occurs		catastrophic failure, i.e. assets crumple
	Thresholds	<1.44 kPa (<30 psf)	1.44 - 1.68 kPa (30-35 psf)	1.68-1.92 kPa (35-40 psf)	> 1.92 kPa (> 40 psf)
Suspended Ash	impact/ damage	resilience maintained	Filter / seals damage	component damage/abrasion/electronic damage	catastrophic failure i.e. turbine destroyed
	Thresholds	light (0.01-0.5 gm^3)	Moderate (0.5-2 gm^3)	Moderate/Intense (1.5-5 gm^3)	Intense (2-8 gm^3)

Table 4.6 Vulnerability model of the storage tanks asset category (shading highlights static pressure and dynamic pressure as the three most damaging hazard impacts for this asset).

Storage Tanks					
		D0	D1	D2	D3
Hazard Type		No Damage	Minor Damage	Major Damage	Destroyed
burial thickness/structural loading weights/static pressure	impact/ damage	resilience maintained	n/a	maximum load standard	Destroyed
	Thresholds	0-1.2 kPa (0-25 psf)	n/a	1.12 kPa (25 psf)	> 1.2 kPa (>25 psf)
Temperature	impact/ damage	resilience maintained	seals damaged	seals destroyed	
	Thresholds	0-80 ˚C	80 - 150 ˚C	150-200 ˚C	>200 ˚C
Laharic dynamic/flow pressure	impact/ damage	resilience maintained	n/a	depends on exposure & type of lahar	catastrophic failure, i.e. tanks crumple/ruptured and flooded
	Thresholds	0-0.05 kPa	n/a	0.05-1 kPa	>1 kPa
PDC dynamic/flow pressure	impact/ damage	resilience maintained	n/a	depends on exposure & type PDC	catastrophic failure i.e. tanks crumple
	Thresholds	0-0.72 kPa (0-15 psf)	n/a	0.72 - 1.72 kPa (15-36 psf)	> 1.72 kPa (>36 psf)
Suspended Ash	impact/ damage	resilience maintained	n/a	Filter / seals damage	n/a
	Thresholds	light (0.01-0.5 gm^3)	n/a	Moderate (0.5-2 gm^3)	n/a

5.0 DEVELOPMENT AND APPLICATION OF A RISK ASSESSMENT FOR THE PETROLEUM SECTOR IN TARANAKI, NEW ZEALAND

5.1 INTRODUCTION

This chapter develops and applies a volcanic risk assessment to the physical assets of the Taranaki petroleum sector. The risk assessment uses a deterministic approach, combining the hazard scenarios developed in Chapter 2, the asset inventory from Chapter 3, and the vulnerability models from Chapter 4 (fulfilling Objectives 1 and 2). Uncertainties captured in the application are addressed in this chapter. Additionally, dependencies on other lifelines and systems are investigated using expert elicitation, and a list of critical dependencies produced.

5.2 APPLICATION OF VOLCANIC RISK ASSESSMENT FOR PETROLEUM SECTOR IN TARANAKI, NEW ZEALAND

The risk assessment methodology used a GIS-based deterministic approach based on the risk assessment approach mentioned in Section 1.5.4, and the two hazard scenarios developed in Chapter 2. The hazard scenarios represent the two typical eruptive styles of Mt. Taranaki, frequent small-magnitude effusive eruptions, and a less frequent large-magnitude explosive eruptions.

The steps taken to combine the three types of assessments (hazards, exposure and vulnerability) and apply the risk assessment for the Taranaki region are to:

a. overlay hazard model (Section 2.3) over the physical petroleum asset inventory (Section 3.4.1)
b. reference the relevant vulnerability models for impacted assets to determine the impact metric value for the relevant asset category and hazard intensity measure (Tables 4.3 – 4.6)
    i. where relevant hazard intensity measures are not available from the hazard models (as discussed in Section 5.2.2), apply arbitrary hazard intensity measures (Table 5.1)
c. assign the highest damage state when an asset is exposed to multiple hazards
d. plot the assets and hazard models for each scenario, showing the final damage state value for all assets.

5.2.1 Overview of the approach used for the volcanic risk assessment for Mt. Taranaki

The hazard assessment (Chapter 2) developed a methodological approach and application to the Taranaki Petroleum Sector to identify the hazards of concern, the styles of a future Mt. Taranaki eruption and built GIS hazard scenarios based on past Mt. Taranaki events. The results drew on existing knowledge from published material, with more recent work providing greater insights into the behaviours of Mt. Taranaki, through the addition of new data and knowledge. The main Mt. Taranaki volcanic hazards the petroleum sector in Taranaki will face are:

- lahars
- ashfall

- PDC
- sector collapses.

The exposure assessment (Chapter 3) developed a methodological approach to build a GIS database of physical petroleum assets and an appropriate classification system. A total of 247 physical petroleum assets were identified, mapped and classified as one of six different asset categorisations, of which four categories (204 assets) are applicable to this study:

- wells
- production facilities
- pipelines
- storage tanks

The development of the asset inventory and asset classification was reliant on petroleum sector expert knowledge, resulting from building strong partnerships and engagement at the expert elicitation workshop.

The vulnerability assessment (Chapter 4) developed a methodological approach and application to the Taranaki Petroleum Sector to produce vulnerability models for the four asset types. A theoretical approach was used for the vulnerability assessment, due to the lack of previous impacts of volcanic hazards on the petroleum sector and untested nature of the results. Expert judgement was used as a critical methodology alongside literature reviews in deriving the models. Intensity scales were selected from a review of the published material, while the theoretical damage thresholds were developed using expert judgement. An expert elicitation workshop allowed collaboration of multiple industry representatives to propose theoretical thresholds at which damage could occur for the various assets from volcanic hazards. A higher level of confidence in the results was achieved by the involvement of expert judgment, compared to a review of published literature only. The vulnerability models represent the relationship between the asset category and the hazard intensity to determine the level of damage likely.

The risk assessment applies the vulnerability models and the various hazard scenarios produced in Chapter 2. The risk assessment results are presented as GIS maps showing the final impact state assigned to each asset. The vulnerability models provide the impact state based on the known asset category and intensity of the hazards at each point for each scenario. Where multiple hazards occur at one location, the maximum impact state across the individual hazards determines the final impact state. For example, if a PDC destroys the asset (impact state D3 – Table 4.1), then any additional damage from ashfall is negligible. For the risk assessment, a critical assumption is made that equipment is in full working order at the time of the eruption. A further assumption is that the industry has had little to no warning and not implemented any volcanic emergency plans. Therefore, no pre-emptive shut down of production has occurred, which represents a worst-case impact scenario.

5.2.2 Application of the volcanic risk assessment for Taranaki petroleum sector

Potential variability in hazard intensity metrics is challenging to derive due to the absence of probabilistic modelling for the PDC and lahar hazards available for use in this thesis. For example, variations in dynamic pressures of PDCs between the main flow and fringe effects are unable to be determined as they were for the Merapi eruption (Jenkins et al., 2013). Therefore, a generic hazard intensity is used in both hazard scenarios, applying a binary “presence or not” assumption. Ashfall intensity variation is represented in the hazard scenarios using thickness. However, as discussed in Chapter 3, the relation between thickness, static pressure, and ashfall concentration over time requires knowledge or assumptions of additional variables, such as ash density, which are absent from available Mt. Taranaki modelling. The presence of ash for some asset types, irrespective of the amount has been shown to cause "major" damage if the system was functioning at the time of the event. Therefore, both a binary and generic value were used, and assets are assumed to be functioning at the onset of ashfall. Scenarios involving a sector collapse are omitted for this risk assessment. Sector collapse events are known to produce binary results on any impacted petroleum assets, except for wells.

Impact metrics were calculated for the four asset categories based on the final vulnerability models (Section 4.2.5) for the hazards of concern to the petroleum sector (Table 5.1). Buildings and industrial users were excluded from the risk assessment, reducing the number of assets in the risk assessment to from 247 to 204 assets. The assigned impact metric values remain the same for the risk assessments of the hazard scenarios, to maintain consistency between the results.

Table 5.1 Assigned impact metric values for the asset categories and hazards. Colours relate to states given in Table 4.1, green- D0, red - D2, black - D3.

Asset type	**Hazard**			
	Lahar	**Ashfall**	**PDC**	**Sector Collapse**
Wellsite	D0	D0	D0	D1
Pipelines (above ground)	D3	D0	D2	D3
Production Facilities	D2	D2	D3	D3
Storage Tanks	D3	D2	D3	D3
Buildings	excluded			
Industrial users	excluded			

The second step overlays the asset data with the scenario, maps using ArcGIS to calculate the impact assessment values of each of the 204 physical petroleum assets in the Taranaki region. This process identifies asset locations that are theoretically exposed to the hazard(s) in each scenario and assigns the final impact state for each asset location; conditioning is applied where multiple hazards impact a single asset location. This process is done for both the small and large eruption hazard scenarios, providing the potential at-risk assets for each scenario (Figure 5.2 and 5.4). The entire process was then repeated combining the two hazard scenarios as a single time-limited event showing the impacted assets from a fast progressing two-phase future Mt. Taranaki eruption hazard scenario. The compounded impact damage is presented (Figure 5.6). Each risk assessment results are preceded by the associated hazard scenario map showing the asset locations (Figures 5.1, 5.3 and 5.5).

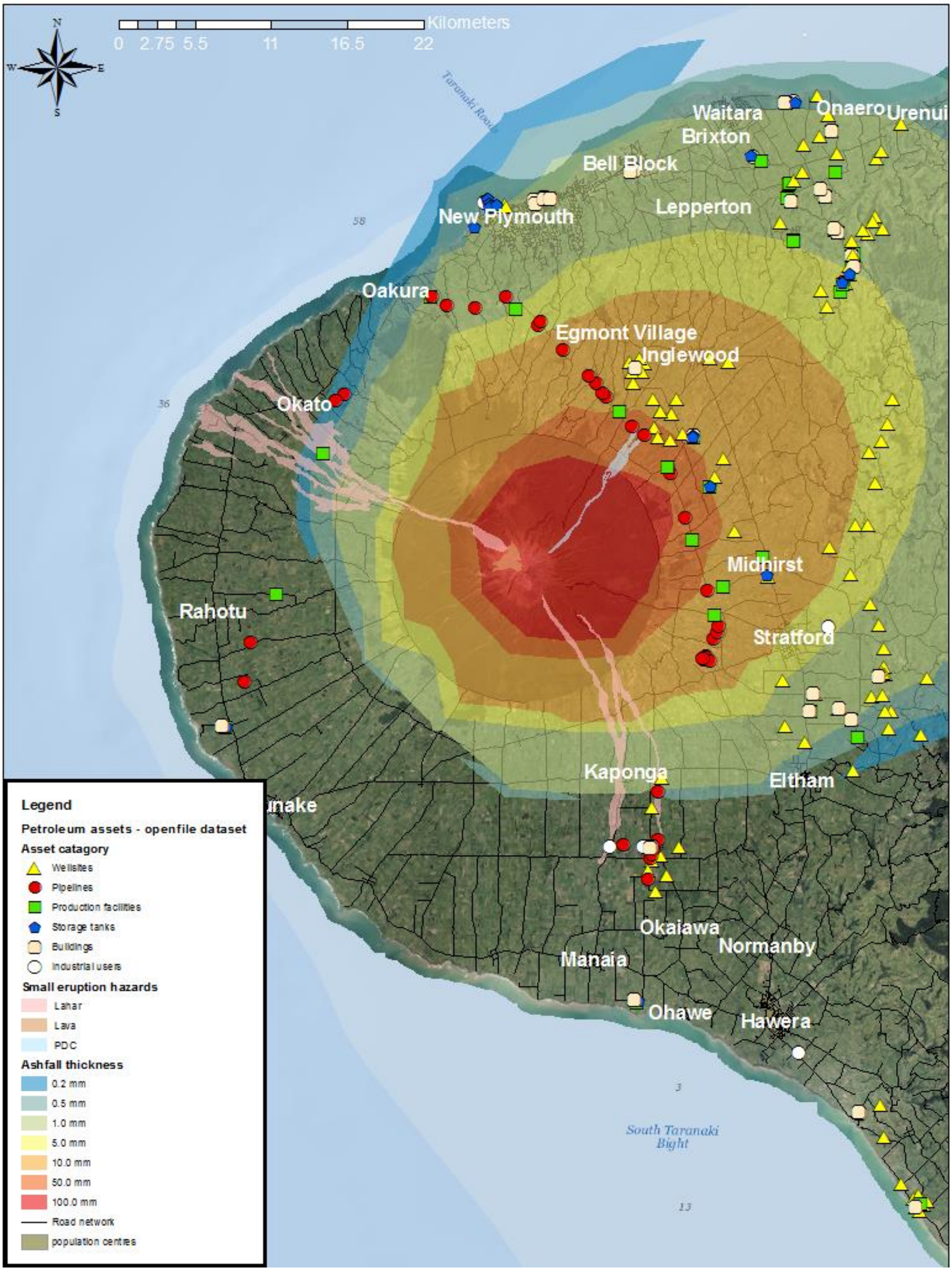

Figure 5.1 Small eruption hazard scenario with locations of the assets and their categories. Note – excluded asset categories are displayed with a white colour.

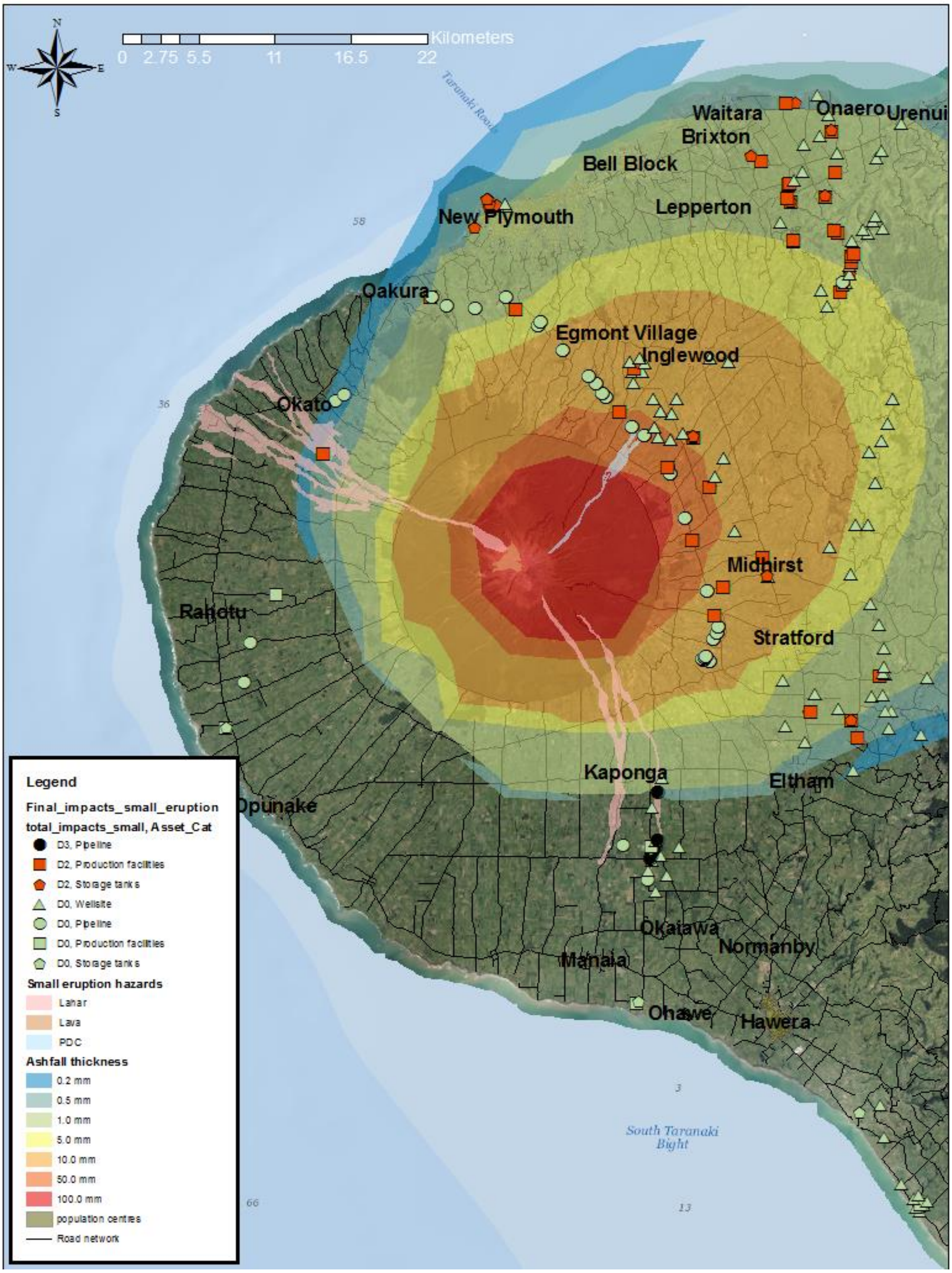

Figure 5.2 Risk assessment results for the small eruption hazard scenario, also showing the hazard layer. Note – assets are subcategories based on the final impact state assigned.

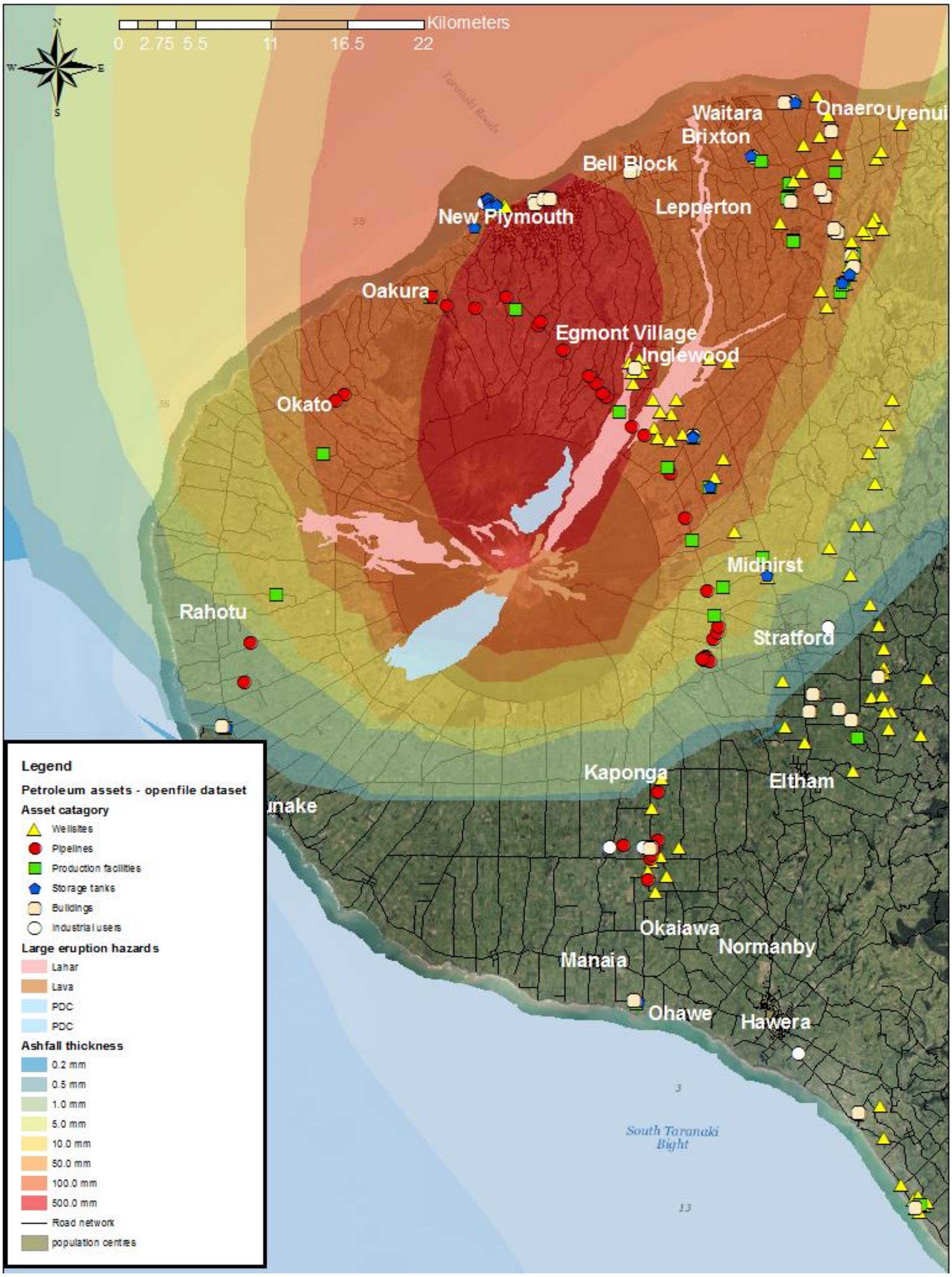

Figure 5.3 Large eruption hazard scenario with locations of assets and their categories. Note – excluded asset categories are displayed with a white colour.

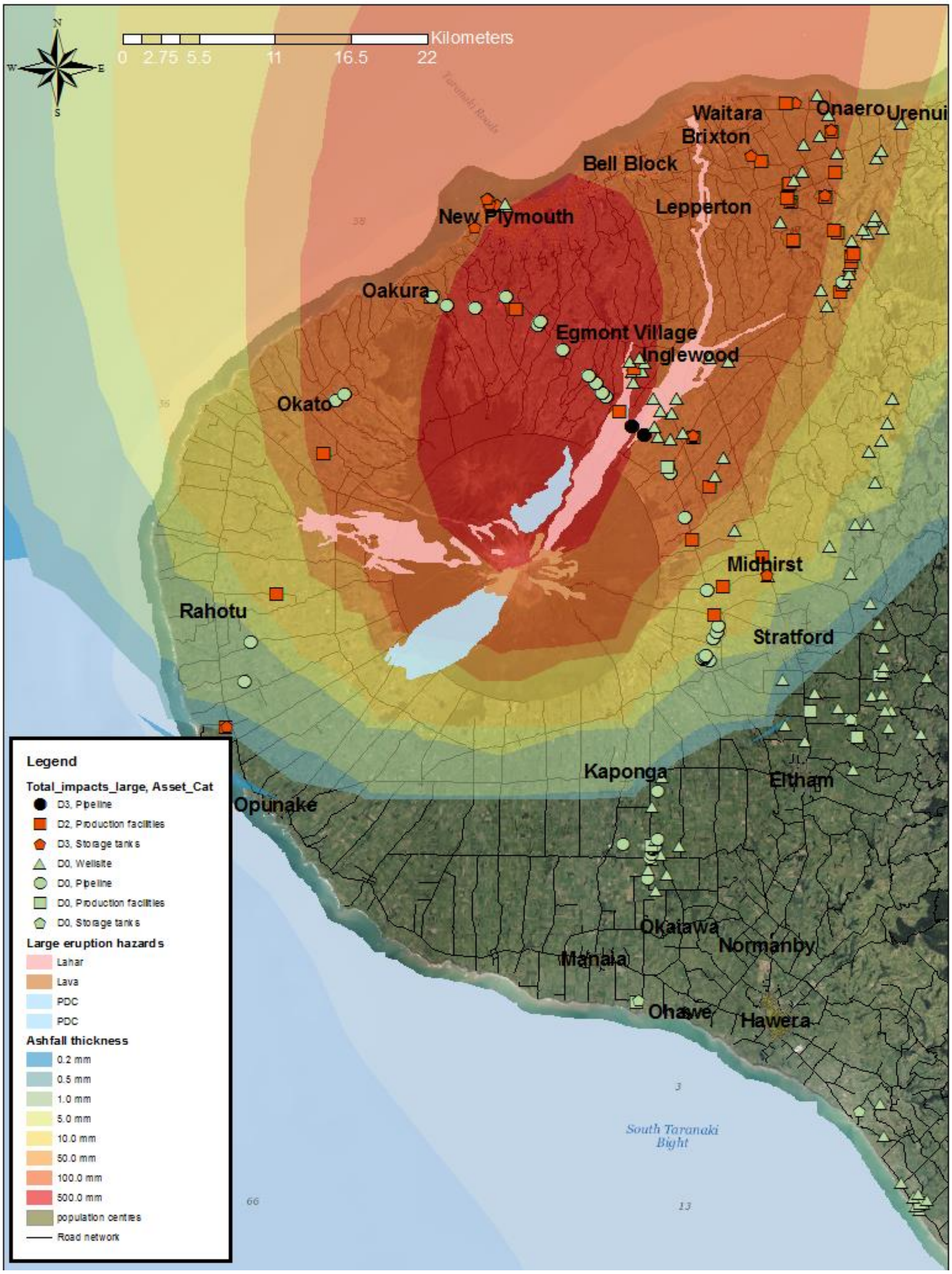

Figure 5.4 Risk assessment results for the large eruption hazard scenario, also showing the hazard layer. Note – assets are subcategories based on the final impact state assigned.

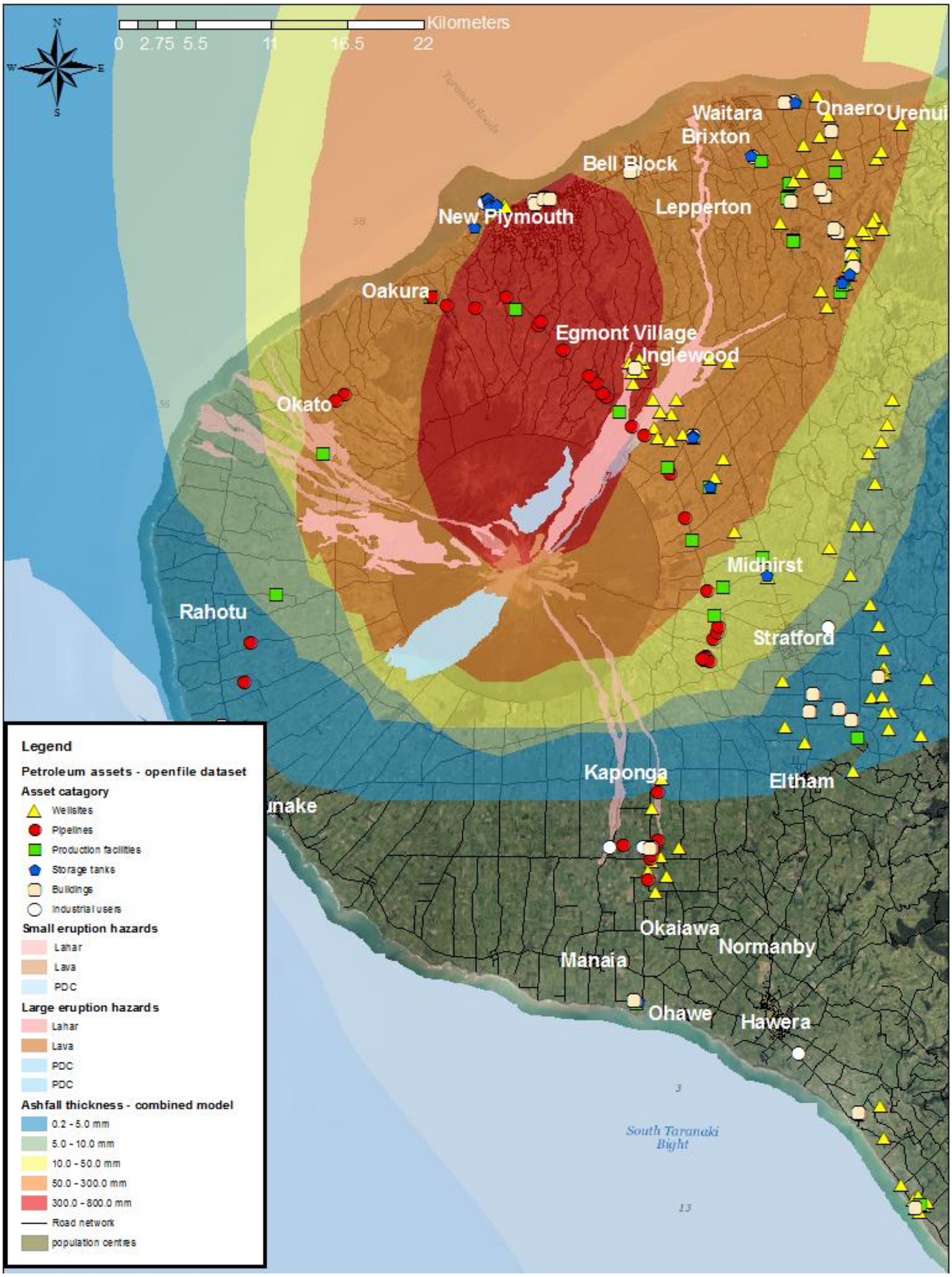

Figure 5.5 Combined hazard scenario (small and large eruptions in a short time period), with locations of assets and their categories. Note – excluded asset categories are displayed with a white colour.

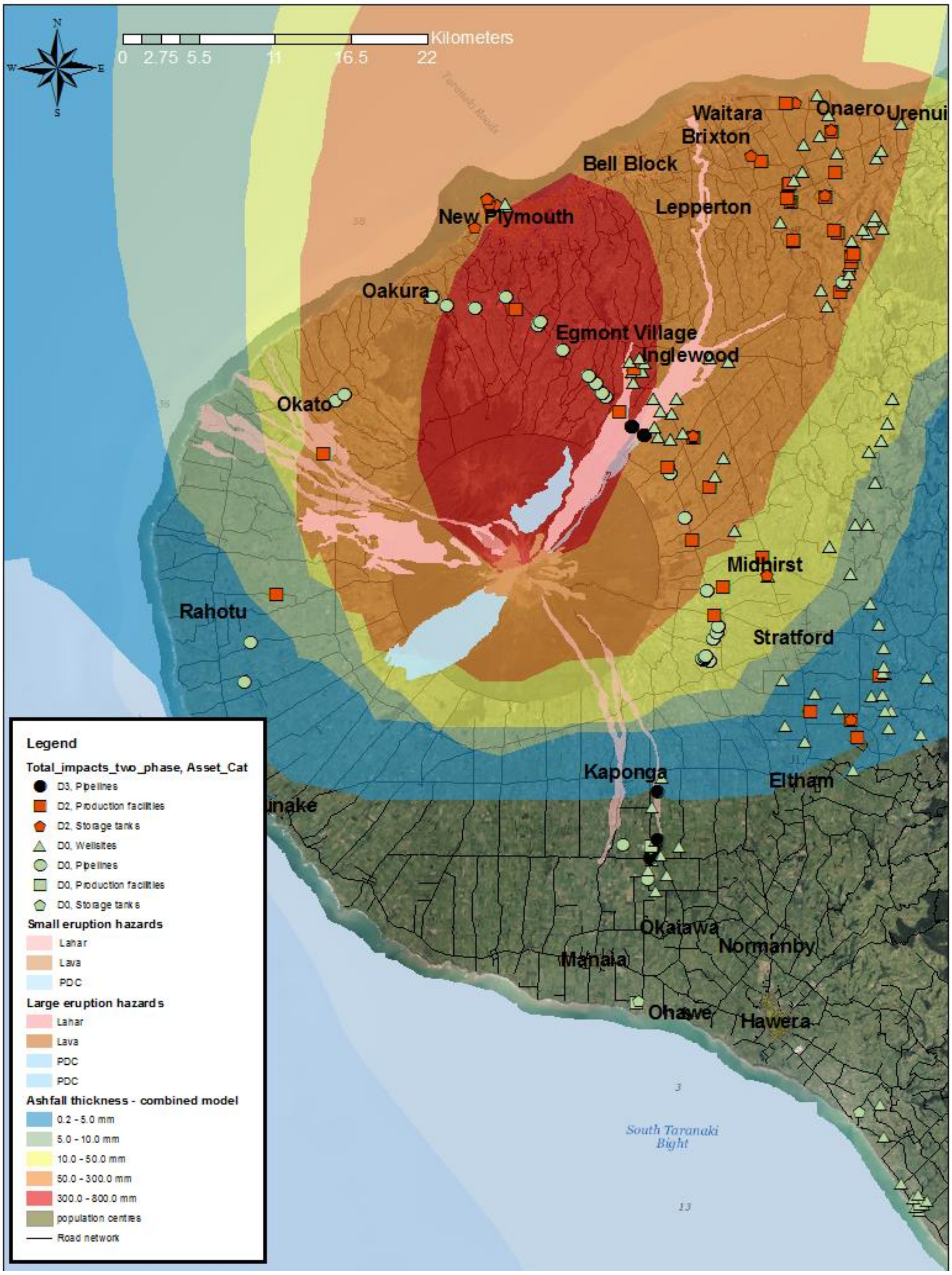

Figure 5.6 Risk assessment results for the combined hazard scenario, also showing the hazard layer. Note – assets are subcategories based on the final impact state assigned.

5.2.3 Results and analysis of volcanic risk assessment results for Taranaki petroleum sector.

5.2.3.1 Risk assessment results

The small eruption hazard scenario (Figure 5.2) occurs at a time where the wind direction deposits the ash to the northeast, with ash falling across much of the region to the north and east of Mt. Taranaki. Ashfall is thickest within the National Park (up to 100 mm) and coating assets from Stratford to Egmont Village in up to 10 mm of ash with small thicknesses reaching as far as Urenui and New Plymouth including the Port with up to 1 mm of ash (Figure 5.2). The ash causes potential major damage to production facilities and storage tanks through abrasion and corrosion impacts. A small PDC runs down an existing drainage channel to the northeast as far as two aerial pipeline crossings but losing sufficient dynamic pressure and temperature not to affect those assets (Figure 5.2). Two lahars occur down existing drainage channels to the northwest and south impacting a production facility and aerial crossings (Figure 5.2). The aerial crossings are destroyed, while the production facility suffers major damage. A summary of the impacted assets is given in Table 5.2 and displayed on the map (Figure 5.2).

Table 5.2 Impacted assets for the small eruption hazard scenario

Risk assessment for the small eruption hazard scenario				
Asset type	**Impact State D0**	**Impact State D1**	**Impact State D2**	**Impact State D3**
Wells	94	0	0	0
Pipelines	34	0	0	5
Production facilities	10	0	33	0
Storage Tanks	4	0	24	0
Total	142	0	57	5

The large eruption hazard scenario (Figure 5.4) occurs at a time where the wind direction deposits the ash to the north, however due to the size ash covers the region to the northwest and northeast also. Thick deposits of up to 800 mm cover a focused ellipse area as far north as the outskirts of New Plymouth, with up to 100mm of ash falling on assets north of Midhurst to Urenui and the Port area (Figure 5.4). Stratford and Midhurst areas receive up to 10 mm of ash. The ash causes potential major damage to production facilities and storage tanks through abrasion and corrosion impacts and will close impacted road networks. Wells and aerial pipeline crossings are not impacted by the ashfall. Major lahars flow to the west and northeast, with the northeast lahar running directly through Inglewood and reach the coast (Figure 5.4), with impacts likely to compromise road bridges, expose buried pipelines and destroy aerial crossings. Wells appear more resilient to the lahar inundations with no damage perceived. Additionally, the volumes will top existing drainage channels and flow across neighbouring fields, roads and buildings and petroleum assets. Two large PDCs occur to the southwest and northeast (Figure 5.4). The southwest PDC extends beyond the National Park, but no petroleum assets are affected. A summary of the impacted assets is given in Table 5.3 and displayed in the map (Figure 5.4).

Table 5.3 Impacted assets for the large eruption hazard scenario

Risk assessment for the large eruption hazard scenario				
Asset type	**Impact State D0**	**Impact State D1**	**Impact State D2**	**Impact State D3**
Wells	94	0	0	0
Pipelines	37	0	0	2
Production facilities	11	0	32	0
Storage Tanks	6	0	22	0
Total	148	0	54	2

The combined eruption hazard scenario (Figure 5.6) compounds the hazards from both the small and large hazard scenarios and causes significant widespread impacts across the entire region with lahars in multiple directs destroying some of the aerial pipeline crossings. Ashfall is widespread with up to 800mm affected Egmont Village and up to 300mm falling at the Port, New Plymouth and Inglewood (Figure 5.6). Lahars take out multiple aerial pipeline crossings and likely to impact road networks (Figure 5.6). However, the total number of assets impacted is very similar to the large eruption except for the additional five aerial crossing destroyed by the small eruption hazard scenario lahar. A summary of the impacted assets is given in Table 5.4 and displayed on the map (Figure 5.6).

Table 5.4 Impacted assets for the combined eruption hazard scenario

Risk assessment for the combined eruption hazard scenario				
Asset type	**Impact State D0**	**Impact State D1**	**Impact State D2**	**Impact State D3**
Wells	94	0	0	0
Pipelines	32	0	0	7
Production facilities	11	0	32	0
Storage Tanks	6	0	22	0
Total	143	0	54	7

5.2.3.2 Risk assessment analysis

This section considers and analyses the results from the application of the risk assessment framework process to the Taranaki petroleum sector. Several volcanic hazards have been identified from the vulnerability models that will potentially cause the most damage to petroleum assets. Table 5.5 shows the identified trend for ash and lahars as the primary volcanic hazards of concern to the petroleum sector.

Table 5.5 Comparison of the volcanic hazards that theoretically cause concern (disruption and damage) to petroleum assets. Red – primary hazard impacts causing the most damage, orange are secondary hazard impacts causing damage.

Wells	Pipelines	Production Facilities (excluding buildings)	Storage Tanks	Buildings (Head office, control rooms)
burial thickness/structural loading weights/static pressure	burial thickness/structural loading weights/static pressure	burial thickness/structural loading weights/static pressure	burial thickness/structural loading weights/static pressure	burial thickness/structural loading weights/static pressure
Temperature	Temperature	Temperature	Temperature	Temperature
Laharic dynamic/flow pressure	Laharic dynamic/flow - variable pressure	Laharic dynamic/flow pressure	Laharic dynamic/flow pressure	Laharic dynamic/flow pressure
PDC dynamic/flow pressure	PDC dynamic/flow - uniform pressure	PDC dynamic/flow pressure	PDC dynamic/flow pressure	PDC dynamic/flow pressure
Suspended Ash	Suspended Ash	Suspended Ash	Suspended Ash	Suspended Ash

Trends can be seen in the results for the three GIS-based risk assessments run for the petroleum sector (Tables 5.2-5.4 and Figures 5.2, 5.4 and 5.6). The pipeline and well asset categories show little to no damage from ash impacts, while production facilities and storage tanks see potential damage or impacts with very small quantities of ash. This is based on equipment being in full working order and that the qualities of the ash cause abrasion and corrosive damage. The impacts may not be immediate, and require more frequent replacement of seals, gaskets and filters, where the increase in replacement is likely to be directly related to the amount of ash the equipment is exposed too. Lahar damage of aerial pipeline crossings and assets near the affected river/streams are seen to cause major damage from all sizes of eruption. PDCs only reach beyond the National Park in the large eruption hazard scenario, and do not affect any petroleum assets. In both the small and large hazard scenario there are at least one production facility system and its associated assets that appears to be unaffected by direct impacts. However, indirect impacts may still impact that system, but the results allow the sector to identify the least impacted system(s). This then allows the petroleum sector and civil defence and emergency management officials to prioritise resources to enable a more rapid resumption of limited production and thus gas supply services from that system. The combined hazard scenario impacts all petroleum production facilities and related systems, resulting in widespread disruption to the gas supply.

The deterministic assessment for Taranaki required an assumption that impact data were consistent values, as hazard impact metrics were not modelled for the locations of assets. Therefore, all assets were assumed to have been impacted by medium to full strength intensity. In reality, lower intensity fringe effects are probable given the distances from the vent. The hazard intensity and distance of assets raised further uncertainty in this methodology, which probabilistic hazard modelling can reduce in future research. Additionally, the methodology developed contained a limited number of hazard scenarios, which were assumed to occur over a few hours to days, with no clean-up or remedial action taken between the events. Improvement of the hazard scenario timeframes will benefit future research focused on recovery of the petroleum sector to a future Mt. Taranaki eruption.

5.2.4 Limitations

All risk assessments will contain uncertainties, from aleatoric (inherent), epistemic (systematic) to ontological (unknown) (Marzocchi & Jordan, 2014). The importance of documenting uncertainties when developing a framework for volcanic fragility and vulnerability functions is highlighted by G. Wilson et al. (2017). Aleatoric uncertainties are associated with the hazard themselves and are beyond the control of the risk manager, as their reduction is not an option. Further research, sampling or data capture can reduce epistemic uncertainties derived from the data, modelling and associated processes and methodologies. Ontological uncertainties, not often mentioned, are the unknown and unexpected uncertainties that are unknown until they occur. For this research, ontological uncertainties are outside the scope of the research. Additionally, consideration of chaos is suggested when applying risk assessments to any industrial sector or systems that involve human decision-making processes (Kirchsteiger, 1999). However, this is difficult to quantify, and while acknowledged, it is beyond the scope of this assessment.

Table 5.6 documents the uncertainties captured during the development of a framework for volcanic risk assessment of the petroleum sector in Chapter 2, which represent areas for reduction in uncertainties in this methodological approach during future work.

Table 5.6 Table of uncertainties and their sources.

Factor	Source of uncertainty
Hazard assessment	Lack of observed and measured hazard intensity matrices
	Incorrect values used for hazard intensities
	Incorrect maximum extents used for hazard maps
	Lack of probabilistic modelling
Exposure assessment	Incorrect categorisation of assets
	Variations within asset categories
	Limited number of assets in categories
	New or missed asset locations
Vulnerability assessment	Determination of threshold values
	Design standards used, especially for older facilities
	Global variations
	Offshore asset variations
	Multiple or continued eruption compounded damage
Risk assessment	Lack of intensity data for some of the hazards and the probability of those hazards occurring.

	The hazard scenarios developed are not able to assess risk through time for the duration of the event and efforts of clean-up and other risk mitigations applied during eruption duration.
	Approach used to apply generic weighting to all assets of the same type
Dependencies	Level of dependency may vary between assets and locations
	Third party assumptions, i.e. contractors

Uncertainty documentation is an important outcome of the volcanic hazard assessment process for Mt. Taranaki. While the "past is a key to the future" for determining future volcanic eruption behaviours, their nature does change through time creating uncertainty in the hazard scenarios produced for future eruptions. A deterministic approach was used for the risk assessment framework, and while this thesis does not address this void in probabilistic data, it identifies priority hazards for future probabilistic modelling research of greatest concern to the petroleum sector, a large contributor to the Taranaki region's economy.

Some of the uncertainties identified in the hazard assessment for Mt. Taranaki include:

- changes in the geochemistry of eruptions through time.
- accuracy in estimating eruptive sizes, volumes and durations from geological records.
- accuracy in determining the full range of volcanic hazards from past eruptions – especially gas volumes that leave no evidence.
- smaller eruptions not captured in the geological record.
- erosion of the geological record by subsequent eruptions, societal development or standard weathering processes.
- accuracy of dating samples and reconstruction of stratigraphic timelines.

Two GIS hazard scenarios were developed as part of the hazard assessment that is based on mapped geological units of past events. This methodological approach came with uncertainties and errors that are acknowledged in Chapter 2. Uncertainties here can be reduced by inferring timeframes and hazard intensity metrics from current or recent analogous eruption timelines. For this initial high-level risk assessment for the petroleum sector, the concern is with the presence or not of a hazard. Therefore, more detailed scenario development was out of scope for this thesis.

Uncertainties arose during the development of the asset inventory and were documented as part of the framework. Access was not available to all petroleum asset locations, which led to assumptions being made as to the asset categories at those locations. For example, offshore facilities. In these cases, information was inferred from photos of the locations from company published material, permit documentation or aerial photos (Google images) to reduce uncertainties. Additionally, the categorisation of assets at a high-level provided a very generic and broad classification. Uncertainties can be reduced by further detailed assessments of sub-category and component of assets, including site-specific assessments to address asset variations between locations.

The exposure assessment and asset categorisation were raised in the expert elicitation workshop discussions and with individual company discussions, identifying which assets were included in asset groupings or excluded from the study altogether. For example, the industry decided that aerial crossings are a subset of pipelines and should not be a categorised separately. Additionally, the attendees perceived that the risks for exploration drilling from volcanic hazards would lead to postponement of exploration activity during any volcanic unrest.

Temporary exploration activity and equipment, such as drilling rigs were therefore deemed out of scope. Petroleum industry discussion concluded that drilling activity would not start or be suspended, and equipment shut down or securely stored, should Mt. Taranaki enter a period of unrest.

The expert elicitation process is a valuable way to generate discussion and capture views from a broad range of industry members but are a limited timeframe. To achieve focused and effective workshops, setting context, expectations, and identifying potential challenges prior to the workshop is critical. One of the most significant barriers encountered during the workshop was detaching the system function from operational dependencies and geographical location. For example, many attendees initially considered the same assets onshore and offshore should be categorised separately. Other groups rapidly grasped the concept of the physical functionality of the assets, irrespective of location. Therefore, concluding that onshore, offshore and pipeline compression stations all contained physical assets that performed the same process and therefore would respond similarly to whichever hazard it encountered. Another example was onshore and offshore wellheads, fundamentally they do the same function, although design variations exist which are based on numerous factors including reservoir pressures. In the same way, groups identified storage tanks and containers are all performing the same process irrespective design, construction or size of the asset. In retrospect, more effort could have been made to help workshop attendees overcome their natural preferences to consider operational aspects or geographical location. There was an incorrect perception that this alternative way of thinking would not be challenging for the attendees; pre-warning attendees and explaining this differing view could have been done before the workshop.

Care was taken during the risk assessment not to focus on the outcomes of the risk assessment or any single scenario, to enable an appreciation that hazards may occur in multiple directions. Additionally, deflecting risk from an individual or specific petroleum assets. Concern was raised that for a single scenario, those members of the industry not impacted would incorrectly assume that they were not at risk from future eruptions. Conversely, a single scenario approach can highlight assets that may not be impacted at all during a future eruption, leading to unnecessary reputational risk to that asset owner. Communicating uncertainty and risk will need to be the focus of future research, gaining a better balance between focusing on a single scenario versus multiple directional risks while managing reputation and public perceptions.

5.3 Dependencies Of The Petroleum Sector

Interdependencies are a key focus for lifeline organisations in disaster risk management, incorporating knowledge of both who relies on the service and whom the service relies on. Rapid recovery post-disruption relies on the clear understanding of lifeline priorities to allocate resources, achieved by identifying dependants of that lifeline, and those whom lifelines depend on to maintain functionality (O'Rourke, 2007). Understanding of lifeline services and their interdependencies has already progressed in New Zealand, with the release of a national lifelines infrastructure vulnerability assessment (New Zealand Lifelines Council, 2017). However, this report highlights gaps in knowledge and understanding of some sectors remain, which this thesis addresses for the upstream petroleum sector. Dependencies on the petroleum sector have been identified through the Critical Contingency Operator (Section

1.4.2). Dependents of extracted oil are overseas markets, and not considered further in this thesis. This thesis identifies the dependencies of the petroleum sector in Taranaki.

Petroleum system dependencies were identified by mapping the various processes that the petroleum sector requires to maintain functionality. A system fault tree visualises such complex systems that have many hidden dependencies. The fault tree approach was used for the risk assessment of a similarly complex sector in the UK, (nuclear power generation) and highlights how quickly complex systems can be impacted at multiple points (Aspinall et al., 2016). The fault tree development requires the use of literature review and expert judgment methods, including individual discussions and site visits. Dependency confirmation and prioritisation can then occur through expert judgment methods such as a workshop to get a sector-wide and generic view for the petroleum sector. Here the hazard scenarios developed in Chapter 2, aid discussions and hazard footprints from a future Mt. Taranaki eruption. Additionally, the expert judgement methodology allows knowledge and sharing of results to be imparted to the petroleum sector, fulfilling Objective 3.

5.3.1 Development of a petroleum system fault tree

The petroleum sector fault tree methodology for the Taranaki sector required interviews, site visits and engagement with industry representatives and some expert judgement. Figure 5.7 illustrates the complexity of the petroleum sector operational systems at a holistic level and highlights the multiple points and volcanic hazards that can impact the petroleum system in Taranaki. Not all the petroleum sector failure points are physical assets, with many operational functionalities impacted through human systems or loss of other critical lifeline services. Fault tree analysis uses top-down logic diagrams to graphically represent pathways within a system that can lead to failures (Clemens, 1993; Larsen, 1974). This analytical technique is commonly used in safety systems analysis to assess risk and identification of undesirable threats or outcomes. The petroleum sector fault tree analysis (Figure 5.7) identified several systems and subsystems which share dependencies on mains power, air quality and distribution networks. These systems will theoretically become disrupted in a future Mt. Taranaki eruption by one or more hazards. Vulnerability models developed in Chapter 4 informed the likely impact of hazards to physical systems, with a review of company emergency management plans and broader literature review informed the likely impacts of volcanic hazards on non-physical systems.

5.3.2 Dependency prioritisation workshop session

The identified dependencies for the Taranaki petroleum sector was prioritised in a session at the expert elicitation workshop (Section 4.2.4). The session included non-technical/engineers, for example, civil defence and other regulatory agencies. Hazard scenarios developed in Chapter 2 were supplemented with an unrest phase preceding the eruption, which was outlined in an eruption timeline for each eruption scenario (Figure 2.4). The intention of this was to allow attendees to assess the indirect impacts of future Mt. Taranaki unrest and eruptions on the petroleum sectors ability to continue to function (fulfilling Objective 3 of the thesis).

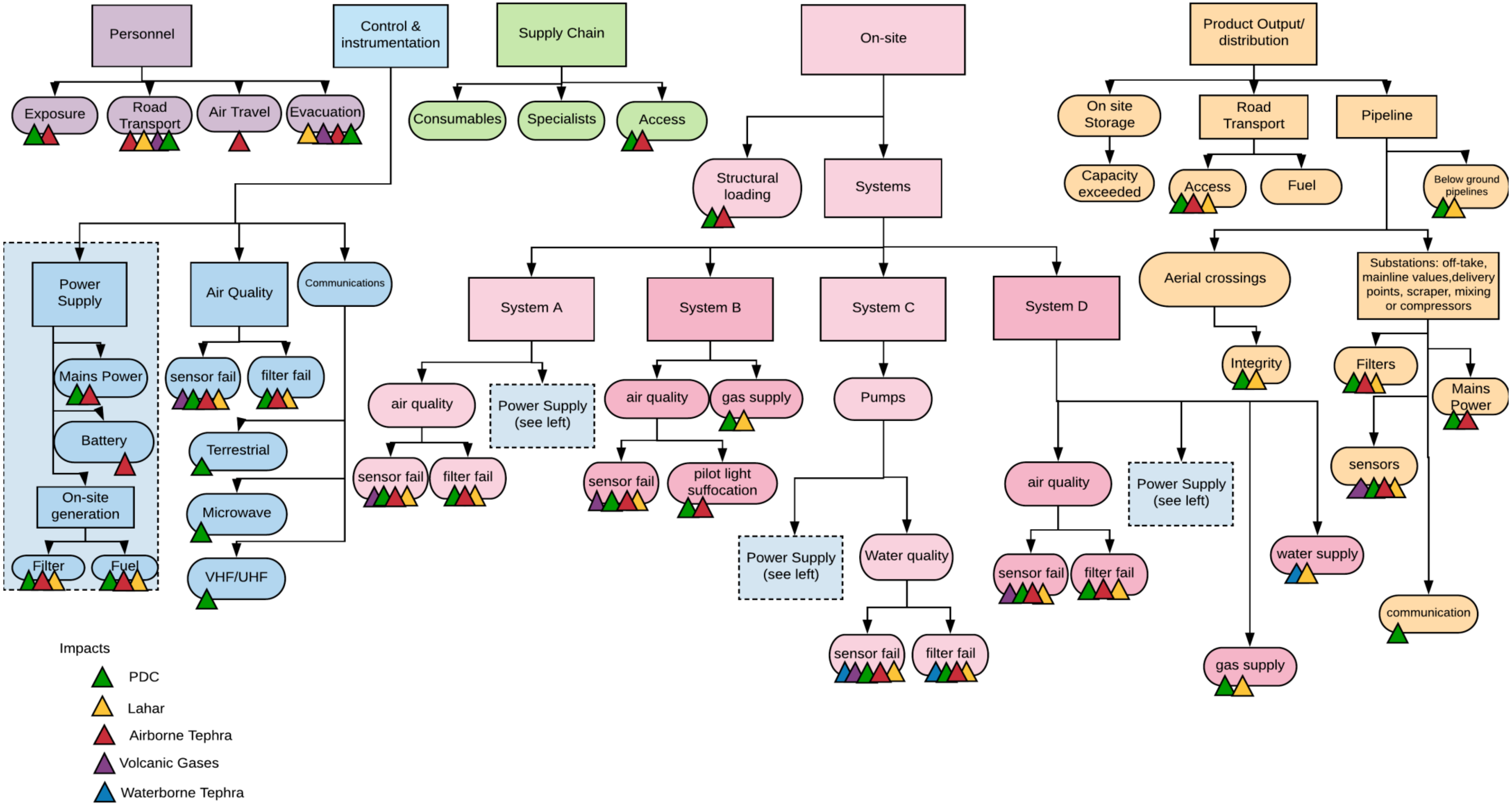

Figure 5.7 Operational petroleum systems fault tree for volcanic hazards.

The workshop considered dependencies of the Taranaki petroleum sector relies on, and prioritised these on the three levels in the New Zealand dependency scale, (given below) developed for the national vulnerability study (New Zealand Lifelines Council, 2017, p. 38):

1. the minimal requirement for service to function
2. important but can partially function and has a full backup
3. required for service to function.

The session produced a list of critical (level 3) dependencies for the Taranaki petroleum sector, Table 5.7. The experts developed a holistic sector approach compared to identifying dependencies for each asset type, which is complex due to the variations between assets at different locations. This approach proved to be more appropriate for the high-level and generic assessment in which the thesis considers the sector. The session enabled spontaneous discussions on response actions and regulation impacts between attendees, allowing greater understanding of decision making impacts the petroleum industry would face in the future unrest of Mt. Taranaki. For example, the impact on assets, access and staff availability from self-evacuations or enforced evacuation zones. Discussions were directed to a more generic discussion as there was a tendency for detailed identification of the specific location of concern, for example, a single bridge in the road network. However, discussions and identification of specific critical points in the networks have been recognised for follow-up work by the Taranaki Civil Defence. Table 5.7 presents the results of the brainstorming session and discussion.

Table 5.7 Workshop outcomes of critical dependencies.

Criticality (Top 4)	**Dependency**	**Comments**
1	Staff/resources	Availability of staff and contractors, which the industry relies heavily on
2	Electricity Networks	Electricity supply/generation network
		Electricity distribution network
3	Water	Supply
		Disposal - sewerage
		Potable water (drinking) for staff
4	Fuel	Diesel & Petrol for road transport
		Integrity of gas and product supply pipelines
	Road networks	Internal and external road systems.
		Weak points in the road network identify bridges as a primary concern.
	Telecommunications Networks	Network Operability - Towers on mountain
		UPS - limited battery supply (hrs)
	AirPort & Sea Port	Servicing of rigs
		Export of product - critical to prevent storage reaching capacity
		Staff transfers and resource supply to rigs
	Regulatory conflict	Conflict of regulations or expectations

The top four dependencies are critically required by the industry to continue to function in a "business as usual" capacity. Disruption to any of the identified dependencies will cause a reduction or halt to the industry's ability to function and thus continue to provide gas into the national network. These assumptions come independently of any physical damage caused by volcanic hazards to the various assets. The session also identified regulatory challenges as a dependency during discussions. Within this topic, a number of key points for further discussions include:

- the impact of evacuation zones on the sector's ability to continue to function
- the need for an advanced warning of evacuations to enable safe shutdown of assets within the evacuation zone
- the Government's expectation of the sector to continue to produce gas,
- what are the realistic recovery times and impacts for the country
- the lack of redundancy as a country for the gas supply
- the interplay of Health and Safety regulations on shutting down facilities pre-eruption and recovery
- lack of volcanic specific hazard assessments or considerations under some of the current legislation and regulatory processes
- the perceived inflexibility of some legislation and regulations in emergencies and recovery phases
- the interplay of industry regulations and legislation with the CDEM Act 2002.

5.3.3 Dependencies analysis

The workshop resulted in a list of the most critical non-physical dependencies for the petroleum sector in Taranaki. Identification of these dependencies informs the petroleum sector of areas to improve their resilience, fulfilling Objective 3 of this thesis. The dependencies session of the workshop provided enlightening discussion for all involved, where the experts identified that the sector works as a system, and all parts need to be operational to continue in a "business as usual" capacity. Disruption to any of the identified dependencies will cause a reduction or halt to the industry ability to function and thus continue to provide gas into to the national network. The experts identified the core dependencies, given in Table 5.7, identifying their top four critical dependencies. This list was also discussed with industry partners who did not attend the workshop, validating the results.

Petroleum sector assets work as an interconnected system, where the failure of a single point within the system, can lead to the entire system shutting down. This may not be immediate, giving time for repairs and allowing production to continue in many instances. The fault tree (Figure 5.7) showed that volcanic hazards could cause multiple impacts which can overwhelm capacity, highlighting the need for more detailed investigations of the petroleum assets at sub-system or component levels. Nevertheless, results of this thesis are valid and allow the industry to identify potential impact problems, which provide an opportunity to consider optimal solutions to mitigate the risks and improve regulations and legislation. Ultimately leading to a more resilient industry, through improved processes, infrastructure design and planning and thus fulfilling Objective 3 of the original aims. A further key point found that incorporation of risk reduction changes to existing infrastructure for companies is a long-term solution, due to the large investment costs. Such changes are frequently adopted over 5/15/30 year development plans to spread costs and resource requirements.

5.3.3.1 Emergency management

Emergency management plan comparison of several Taranaki petroleum companies, that cannot be named due to confidentiality reasons, highlighted the strong emphasis on the protection of staff and the environment ahead of the physical assets. This finding is consistent with New Zealand legislation governing Health and Safety in the workplace. Plans are varied and fundamental at best, due to lack of experience of volcanic events. The overwhelming appreciation from the emergency planning across the industry was of risk avoidance, achieved by plans to stop production and purge assets and pipelines of hydrocarbon products at the onset of a volcanic eruption event, in some case at signs of unrest (VAL 2). With the aim of providing sufficient time for assets to be shut down before ash or other hazards cause damage or create an environmental disaster. However, from analogous eruptions, such as Montserrat Volcano, 1995, or Agung Volcano eruption, 2017, unrest periods can last many months before an eruption, with the eruption then continuing for months or years (Relifweb, n.d.; Robertson et al., 2000; Sparks & Cashman, 2013). The entire sector cannot take a cautious early-shut down approach not knowing if unrest will led to an eruption in days, weeks, months or at all. The concern with premptive shutdowns are that there is only 4-5 days of gas supply available in the pipeline (WorleyParsons, 2014) and a requirement under the Civil Defence and Emergency Management Act 2013 or the Gas Act 1992 to continue the supply of gas as a critical service to New Zealand. The risk is heightened by the current situation where all domestic producing gas fields are in the shadow of Mt. Taranaki and exposed directly or indirectly to volcanic eruption hazards. While a short-term (<24 hr) shut down of gas production at one or more sites is a frequent occurrence, the country has not fully appreciated the implications of a complete shutdown of all gas production for some weeks. This scenario is currently a realistic possibility in the event of a future Mt. Taranaki eruption. Additionally, it is probable that magmatic unrest may occur, where VAL2 reached and maintained for some weeks without an actual eruption. Therefore, the industry will rely on the science community to deliver regular updates and close monitoring of Mt. Taranaki, while balancing the need to continue production with the safety of staff. There are no easy answers, and these concerns can be flushed out in future studies around response and recovery actions, planning and timing, which this thesis provides a springboard for.

5.3.3.2 Regulatory challenges

The regulatory challenges identified as a dependency was acknowledged as an important factor for recovery. Where the impact that regulatory challenges could hinder rapid recovery and smooth governance under emergency powers. Such policy and legislation challenges hindered an efficient recovery in Christchurch following the 2010 and 2011 Earthquakes (Wilkinson, Crampton, & Krupp, 2018). Good pre-event recovery and response planning for legislative barriers is critical if the same mistakes are to be avoided. This thesis identifies recovery challenges as a key future study area for the petroleum sector. The petroleum sector regulatory challenges are an important finding for government and policymakers to consider with urgency and highlights pre-event recovery planning for the petroleum sector will be critical to improve resiliency and reduce disruption to the nations gas supply. A specific concern was raised about expectations and defining a clear expectation with the government of what is anticipated following such an event of the petroleum sector, with input from the sector around realistic timeframes. This will allow improved pre-event response and recovery planning and inform the government of potentially lengthy recovery periods leading to consideration of risk mitigation options for both the petroleum sector and the government. The dependency results also conflict with the results provided by stage one of the national vulnerability study (New Zealand Lifelines Council, 2017). However, this is unsurprising, as previous studies have only focused on the mid and downstream aspects of the petroleum sector, while this research identifies a gap and results for the previously unstudied upstream sector. The inclusion of these results in future revisions of New Zealand's vulnerability study is critical.

5.4 SUMMARY

The key points from the methodology for development and application of a volcanic risk assessment for the petroleum sector of Taranaki are as follows:

- The risk assessment methodology applied is a limited deterministic approach because of hazard scenarios developed in Chapter 2. This meets Objectives 2 and 3 of this thesis.
- Documentation of the uncertainties and their sources is an essential aspect of the framework for a volcanic risk assessment of the petroleum sector, to improve resilience understanding for the petroleum sector.
- The workshop offered an ideal opportunity for collaborative discussion and relationship building, especially between civil defence and the industry, (fulfilling Objective 3 of this thesis). A key discussion was about evacuation zones and how the emplacement and enforcement of these will become a crucial factor for industry planning and consideration for civil defence planning.
- The workshop identified regulatory challenges that require urgent consideration, where some critical aspects need to be considered in the short term by policymakers, as the resolution is required before any volcanic unrest occurs.

6.0 CONCLUSIONS

This chapter concludes the thesis by summarising the key findings relating to the thesis aims and makes recommendations for future work.

The sector of interest is the New Zealand petroleum exploration and production, or upstream sector, based in the Taranaki region is directly at risk from volcanic hazards from Mt. Taranaki. The sector is located on the slopes of Mt. Taranaki, a dormant stratovolcano with a 50-81% probability of a new eruption phase beginning within the next 50 years (Damaschke, Cronin, & Bebbington, 2017; Green et al., 2013; Turner et al., 2009). The sector provides a vital input to the Taranaki and New Zealand economy through exports of petroleum products and the supply of the entire North Island residential reticulated gas resource. Additionally, the sector provides essential methanol production, supports the dairy industry, and through transformation provides 15% of the country's electricity (New Zealand Government, 2017). However, there is a very low awareness of the volcanic risk within the Taranaki public (Finnis et al., 2004). This thesis has found these perceptions extend to the petroleum sector, leading to struthious behaviours in planning for volcanic eruptions and hazard impacts (Section 5.3.3.1). The petroleum sector in New Zealand considers volcanic hazards as low or "hypothetical" in the formal risk frequency class, based on the New Zealand Risk Management Standards (WorleyParsons, 2014, p. 83). Given the revised probability of an eruption, the anticipated lifespan of petroleum infrastructure, and the likely consequences to the petroleum industry in a future eruption (as assessed in this thesis) the volcanic risk ranking should be considered "occasional" or at worst "unlikely". While the consequences remain the same at "Severe to Catastrophic", depending on the size of the eruption, the change in frequency classes increases the risk ranking to categories that now require risk treatment actions (WorleyParsons, 2014, p. 84). Additionally, the 2014 government-led study on potential disruptions to New Zealand's gas supply downplayed the volcanic risk and considered outages to main gas producing fields or pipeline in isolation (WorleyParsons, 2014). Consequently, the sector appears to have taken very limited, if any, planning for a future volcanic crisis within individual companies or sector-wide. This Master of Science thesis research directly addresses this gap.

This Master of Science thesis research has achieved its objectives (Section 1.2) by:

- developing a methodology for volcanic risk assessment of the petroleum exploration and production sector, using standardised risk management practices at a holistic level. This involved developing a repeatable risk assessment framework for the petroleum sector, consistent with current best practice methods of risk assessments for volcanic hazards (Objective 1).
- applying the developed methodology, using new volcanic eruption scenarios, for Mt. Taranaki to undertake a physical impact assessment of the petroleum exploration and production sector in the Taranaki region. This included the development of vulnerability models for the petroleum sector (Objectives 2 & 3).
- engagement of petroleum sector and an expert elicitation workshop that imparted scientific knowledge of the volcanic hazards associated with Mt. Taranaki and the likely direct and indirect impacts (Objective 3).
- assessment of volcanic vulnerabilities, likely impacts, and network dependencies for a volcanic crisis that can be used to inform volcanic mitigation and resilience development strategies in the petroleum sector (Objective 3).

The thesis results provide a foundation for future studies, and a catalyst for the petroleum sector to undertake their own risk review processes for the development of risk treatment activities.

The research has additionally contributed to the Natural Hazard Research Platform – “quantifying exposure to specific and multiple volcanic hazards” project. The results not only expedite further research for this sector but fill a gap in knowledge for New Zealand’s lifeline infrastructure vulnerability assessment of the nation’s gas supply, a critical lifeline service.

6.1 KEY FINDINGS

The thesis results have identified the following key findings:

- Awareness of volcanic risk, impacts of volcanic hazards and probability of a future eruption is low within the Taranaki petroleum sector.

- The risks to New Zealand’s gas supply from a future Mt. Taranaki eruption have also been underestimated.

- The impact of regulations on the petroleum sectors’ ability to operate during a volcanic crisis and recover rapidly has been identified as a potential risk.

- Future eruptions from Mt Taranaki will likely cause extensive damage and disruption to the Taranaki petroleum sector, as found from using a structured volcanic risk assessment approach for two Taranaki eruption scenarios.

- Multiple dependencies and interdependences with other essential services, components and organisations have been identified for the Taranaki petroleum sector with respect to a volcanic crisis.

The research found that volcanic hazards will impact the petroleum sector in multiple ways. The physical petroleum assets around Taranaki work as a system, where volcanic hazards cause disruption or damage to individual assets or dependencies. Which in turn disrupts production leading to the national gas supply being impacted. Such disruption is more likely for prolonged unrest or effusive eruption activity which continues beyond 3-4 days, or if a larger explosive eruption occurs. Sector collapse events are directional and have the potential to cause either minimal disruption or major disruption, depending on the direction of collapse. Recovery of the petroleum sector from a future volcanic eruption was found to be a key area for future research, including regulatory challenges identified by the petroleum sector during this research (Section 5.3.3).

Should prolonged unrest occur a “new normal” way of working would likely be adopted by the industry, given their commitments and requirement to continue to supply gas. This new normal would require changes to the regulatory regimes to allow ‘business as usual’ to continue during the volcanic unrest and prolonged eruption episodes. Such shifts in work practices tend only to occur in the window of opportunity provided by major disruption or damaging impact, as seen in many disasters (Birkmann et al., 2010). However, the industry will only be able to make effective use of such windows of opportunity if they are prepared in advance through pre-event recovery planning. While this thesis does not address recovery actions, timeframes and challenges, it provides a springboard for future research into this area to occur. Effective pre-event response and recovery planning will involve the government, regulators and policymakers to review legislation and further discussions with operators around the operational challenges identified in the workshop. The importance of WorkSafe NZ in the role of recovery and even pre-eruption shutdowns was the topic of robust conversations that need expanding on in further discussions. Additional discussions may also reveal further challenges that can be resolved or give clear guidance in advance of a disaster or disruption occurring. The challenges already identified are wide-ranging and highlight the vulnerability of the country's gas supply all being from a single region that has very little redundancy built into the systems. Additionally, the increased risk from recent research of Mt. Taranaki required a change in risk ranking for volcanic hazards and review of the subsequent impacts in urgency for the petroleum sector. Petroleum companies need then to enhance and review their risk management approaches to volcanic hazards to reduce the volcanic risk to acceptable levels or 'as low as reasonably practicable' (ALARP). This recommended change in the risk ranking for volcanism in the Taranaki region also has impacts for relevant legislation and regulations that deal with risk for this sector. These changes require an underpinning risk assessment for volcanic hazards, which this thesis provides at a high-level. This then allows a spring-board for future studies and the development of risk treatment actions.

The development of relationships with the petroleum sector was essential to gain an accurate insight of the complexity of the sector and draw on expert judgement to support the development of a risk assessment framework. Similarly, if the risk assessment framework methodology developed here is adapted by other sectors, close relationships will remain important to successful application and buy-in. The Taranaki Petroleum sector also gained from the experiential process by increasing their knowledge and understanding of Mt. Taranaki and its volcanic hazards. In some cases, individuals had an incorrect view that Mt. Taranaki was extinct, leading to a struthious approach to volcanic risks in the Taranaki petroleum sector. The expert elicitation workshop offered an ideal opportunity for collaborative discussion and relationship building, especially between civil defence and the industry. One key point raised in discussions was around evacuation zones and how the emplacement and enforcement of these will become a valuable factor for industry planning and consideration for civil defence planning. The sector's understanding of volcanic hazards has grown considerably through engagement with this project, and they are now more comfortable with the potential of future volcanic unrest and eruption hazards for Mt. Taranaki. The sector has learnt how volcanic hazards impact physical infrastructure, and that the hazards also cause indirect operational dependencies. Recovery actions and timeframes are out of scope for this project. However, future research can focus on the interplay between repeated events and how this would impact the petroleum sector in the longer term. The sector will benefit further from a multi-operator exercise soon, to test their internal procedures and policies and if expanded can consider post-eruption recovery actions and timeframes.

6.2 RECOMMENDATIONS

To better mitigate the risks and to further industry resilience, research by academic organisations in partnership with industry is a key component of future work.

Recommendations of key areas for future research are:

1. Reducing uncertainty and expanding the knowledge base of Taranaki petroleum assets by:
    a. Probabilistic hazard modelling for Mt. Taranaki, prioritising ashfall and lahar hazards, with a focus on lahar scouring.

b. Understanding of thresholds for petroleum infrastructure by undertaking more detailed asset and site-specific component level studies. Particularly on key assets such as storage tanks, pipelines and components such as wiring and seals to identify further risk mitigation options.

Incorporating GIS is essential for future volcanic risk assessments to enable visual outputs for communicating results to stakeholders, scientific communities or as inputs for risk modelling using specialist software.

Further research on risk communication for Mt. Taranaki hazards and impacted industries, balancing single scenario versus multiple scenario risk analysis without compromising reputational risk.

Examining recovery processes, regulations and considerations for the Taranaki petroleum sector to identify barriers and limitations for rapid recovery. Consider collaborative scenario-based exercises for the response and recovery phases of an eruption event to inform pre-event response and recovery planning. Additionally, when planning full facility shut-downs, build in company-based exercises that will test eruption response plans and gauge the time required to undertake the required actions.

The industry looks to the scientific community to provide early warning and detailed hazard information that can be enhanced through industry-science collaboration around baseline data. For example:

a. Funding maintenance and improvements of the Geonet seismograph and GPS stations for seismic, volcanic and landslide hazards.

b. Gathering and sharing LIDAR survey data and funding surveys to infill gaps in the survey to get a full Taranaki peninsula dataset for rapid landslide, earthquake and volcanic hazard identification.

6.3 Future Work

This research identifies the upstream petroleum sector as having a vital role in supplying one of New Zealand’s critical lifeline services, which overlooked until now, has received little to no known volcanic risk assessment research. The research has also developed a risk assessment framework for volcanic risk assessment for a new sector. In doing so has achieved valuable experiential outcomes for the Taranaki petroleum sector in starting conversations that led to a greater awareness of volcanic risks to their staff, operations and physical assets. The key is to now continue the momentum of this raised awareness through further research with the industry as a key partner in this research and supporting them to consider and action risk reduction (mitigation) options, as individual companies or through collaboration as an entire sector. The central and local government also have a role in risk reduction, readiness and pre-event recovery planning actions for the petroleum sector through identification and changes to policies, legislation and regulation that will cause barriers to uninterrupted gas supplies for New Zealand.

When determining vulnerabilities and hazard assessments, it is critical to keep in mind that results are not static, requiring regular revision as infrastructure changes through time, and hazard modelling is improved. As such, it is pertinent to state that this research is a high-level first attempt at a risk assessment and should be likened to a springboard to further work and improved knowledge of and for the industry. During the research, numerous areas for further research were identified as well as suggestions for potential risk reduction and readiness actions. However, the lists are not exhaustive, and only a selection of the critical points are captured in this thesis.

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APPENDICES

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A1.0 APPENDIX A – ASSET CLASSIFICATION EXAMPLES

A1.1 WELLS (WELL-HEADS AND STACKS) – TYPE 1

Stand-alone Well pad, where the well may be producing, injecting or have been either shut-in, suspended or abandoned. Well pad, head and stack construction vary between the wells depending on the depth and product mix. In some cases, artificial lift is required to help the product (oil) flow to the surface, and this may require additional equipment. Examples of the iconic “nodding donkey” are rare across the region, with the majority of a “Christmas tree” stack design, which incorporate hydraulic or pneumatic values. Where pneumatic values are present, associated air compression units are required. These can only operate in clean air environments as ash fall will clog the filters. Some well sites are designated deep water injection sites for wastewater, with associated closed water storage tanks and pumps.

Where well sites have production equipment located on the pad, a classification of “production facilities” is assigned. However, the associated production may just be pre-processing rather than full-scale production. The “production facilities” assignment generated some discussion around what processing is compared to the full production sites. For this research, well sites are nominally stand alone with limited associated equipment. Where processing occurs, these have been classified as production sites, noting the vast variation in volumes and scale among assets in this category. Consideration was given to a third category, but a more simplistic approach was sought for this research noting that the variation is related to the volumes managed at each site. In which case, the likely impacts would be similar to the production sites, making the grouping under production acceptable for this research.

Example Photos:

Figure A1.1 Iconic “nodding donkey” well

Figure A1.2 “Christmas tree” wellhead stack

Figure A1.3 Multiple “Christmas tree” wellhead stacks and associated gathering pipelines and monitoring equipment

Interdependencies Electricity – for sites with air compressors or water pumps.

Hazard impacts: Static Pressure (Structural loading) – most well sites are relatively robust to ash fall and burial as there is little surface area for ash to accumulate upon. Unless burial is with cemented deposits or air compressors are used, most wells will be able to be easily cleaned and continue to perform. Closed lid water tanks for deep water injection wells will benefit from more detailed further research to understand their structural loading capacities.

Ash concentration - for sites with air compressors units, the finer ash will quickly block the filter and cause damage to the pumps due to the abrasive nature of ash.

Temperature – there will be a point at which the temperature could weld/melt valves on a "Christmas tree" structure. Further research is required to understand these thresholds. Noting there are very few locations where PDCs are likely to impact the current asset stock.

Dynamic pressure – Well heads are designed to be very robust and depending on the design, materials used, and construction a range of thresholds at which dynamic pressure could potentially shear off the wellhead structures needs to be understood through further research. Due to the individual nature of the wells results are likely to vary from well to well. Note that where lahars and PDC are smaller and confined to the river/stream channels, sites are likely only to be subjected to fringe or overflow from the rivers and streams and dynamic pressures are less than in the river channels. However, larger flows of greater volume will cover wider areas beyond the river/stream channels, with high flow rates and speeds.

For pyroclastic density flows rather than currents, only a limited number of the current assets mapped are likely to be at risk. Additional research and modelling will further define the risk for each of these sites.

Note however that if subjected to a sector collapse there is likely to be considerable damage both above and below ground to any wellhead structures impacted.

A1.2 PIPELINES – TYPE 2

Pipelines associated with the petroleum industry come in a wide variety of sizes, materials, diameters and carry a range of products. For this research, we are looking at the production pipelines and transmission pipelines up to the offtake or delivery points at which point, pipeline ownership is transferred to the distribution network and is out of scope for this research.

However, despite being out of scope, the buried pipelines have been mapped to give contact to the petroleum system.

Additionally, within the various production sites, there will be many kms of pipeline above ground, which are considered under the "production site" asset category. Note that for this research, the individual component level detail is not dealt with and suggested as an area for further research.

Around New Zealand and especially the Taranaki Region, buried pipelines form a complex network, where ownership and maintenance of the pipelines varies.

In several places, the pipes come above ground for aerial crossing points above rivers or streams. A separate "special pipeline crossing" asset category is used for these.

The main transmission lines and their lateral lines have been given numerical designations, for example:

Main Trunk	Informal name	Lateral lines
100	Kapuni - South	101, 102, etc
200	Kapuni - North	201, 202, etc
300	Kapuni - Frankley road	301, 302, etc
400	Maui	401, 402 etc
500	Bay of Plenty	501, 502, etc
600	South	601, 602, etc
700	Central	701, 702 etc

In addition to the transmission lines, separate water, condensate and mixed product gathering lines also exist within the network. These pipelines have a variety of diameters depending on the product and flow volumes, from ~100-500 mm, with a range of pipe thicknesses, materials operating pressure ranges, burial depths, coatings and configurations that make a single fragility function or vulnerability matrix for all pipelines unrealistic.

Further research and work are required to understand what are the parameters that affect vulnerability to volcanic hazards and then develop specific functions for the relevant pipeline groupings. This work will require close work with pipeline engineers.

Interdependencies

Pipelines depend on the supply of gas into the network to maintain a minimum operational pressure.

Hazard impacts:

Not investigated in the scope of this research.

Note however that if subjected to a sector collapse there is likely to be considerable damage to both above and below ground pipeline in its path. Further research can draw on the landslide damage at an elbow joint that was experienced in 2011.

Example photo:

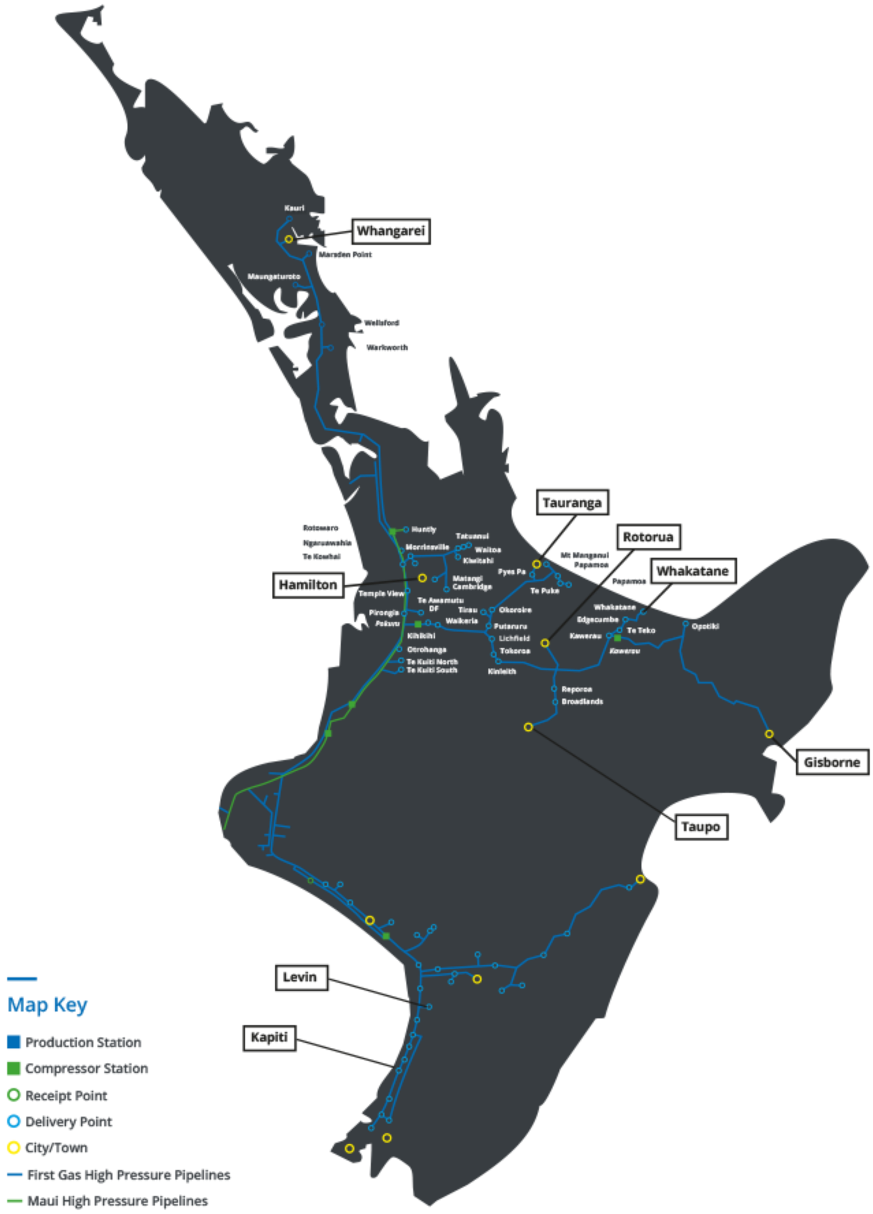


Figure A1.4 Network map of the FirstGas transmission pipeline in NZ (FirstGas, n.d).

A1.2.1 Pipelines – Aerial subgroup crossings – Type 2A

As a subset of the pipeline category, where pipelines come above ground for aerial crossings, normally over rivers, there are three or four main construction types: trestle (caged), single pipe, structurally supported or attached to a bridge.

Each variety will have a variation in structural strength to dynamic pressures of PDC, lahars and flooding associated with volcanic hazards, including the rare but possible sector collapse scenario. Therefore, for this research, a range of possible thresholds have been used, and we have noted that some crossings do sit within a 20-km zone of the vent (Zone A) where PDCs may occur.

Due to many crossings, crossing types and pipeline, the recommendation of further site-specific research in conjunction with more detailed PDC, lahar and sector collapse modelling for many streams and rivers that are feed from the steep slopes of Mt. Taranaki is made.

Example photos:

Figure A1.5 Private access bridge carrying various pipelines suspended above the Waitara River.

Figure A1.6 Three pipelines are crossing the Piakau Stream, using trestle crossing construction style.

Interdependencies None

Hazard impacts:

Static Pressure (Structural loading) – Aerial crossings not attached to bridges have limited surface area in which to accumulate ash deposits. Additionally, given the curvature of the pipeline, ashfall is likely to slide off before it creates any issues. However, where pipes are attached to bridges like the photo above, the structure of the bridge and weight bearing capacity will influence the vulnerability to accumulations of ash, particularly if wet. A recommendation for further site-specific research for at-risk sites is made.

Temperature – From known operational temperature limits for pipelines, exposure to temperatures of above 45^{o}C for more than 15 mins will require reduced pressure and inspections for stress fracturing as a minimum. Temperatures of pyroclastic density currents and flows will exceed these thresholds. Therefore, the crossings identified in the PDC risk zone (Zone A) require further detailed risk assessments, with risk reduction changes implemented at the earliest opportunity.

Dynamic pressure – Aerial crossings are exceptionally vulnerable to the dynamic pressures achieved with lahars, PDCs and even sector collapses. The repeated influx of sediments, water and debris (rock and plant material) that combines within a lahar, causes dynamic pressures that can damage structures crossing rivers and streams that they meet on their routes. Lahars also exhibit erosional characteristics that can cause erosion to depths well beyond the current industry burial depths. Thus, exposing buried pipes that run under rivers when large lahars occur. Further risk modelling work is recommended for the numerous Mt. Taranaki fed rivers and streams. Examples of lahar erosion and pipeline exposure were evident following the 1990 Mt Redoubt eruption at the Drift River terminal, Alaska.

Ash concentration – finer ash is unlikely to be an issue with this asset type as the pipeline is static with no moving parts. However, larger tephra may cause ballistic like impact on an exposed pipeline that requires further investigation depending on the pipe material, coating, pressure and if caged or not. Note that interaction between the various coatings and the corrosive nature of ash may also cause issues if not cleaned frequently.

Failure of the main transmission pipelines can create considerable widespread economic and social disruption. Without the pipeline network intact, some production companies would have to curtail production with nowhere to put the gas, due to limited onsite storage and lack of alternative uses.

A1.2.2 Pipelines – Above Ground Assets – Type 2B and 3

Due to components of many of these assets types being consistent with components seen in production facilities the expert elicitation workshop suggested these be categorised the same as a seen in production facility. Above ground asset sub-type can be a combination of any of the following: off-take, mainline values, delivery points, scraper, mixing or compressors.

Mainline valves – The purpose of these is to isolate a section of the main transmission network by valves either end of the section. These are located at a maximum distance of 32 km along the pipeline network, with upgrades ongoing to convert manual to remote operation monitoring and control. While they use low-volt electricity for the communication and sensors, they can operate in a safe mode if mains power fails. To close off a section of the main transmission network valves either end of the section will need to be closed either remotely or manually.

Delivery points (off-take) – These allow gas to enter the distribution network, which operates at a lower pressure. To overcome the thermodynamic temperature loss when the gas pressure reduces, the gas is first heated. The heat generated by a variety of methods including gas turbines are susceptible to ash corrosion damage.

The above ground assets consist of various pressure valves that can be activated remotely or manually, with a fail closed designation above ground. The set-up provides resilience in the system, where if individual above ground assets are lost the underground buried main transmission pipeline remains able to continue to operate. So even with the loss of electricity or telecommunications valves can be manually closed or will close if pressure high/low trigger thresholds are reached.

Scrapper Stations – These are locations where “PIG” launchers and traps occur along the pipe networks. These are points in the network where “PIGS” enter and exit the pipelines. “PIGS” are maintenance devices used to inspect and clean the interior of the pipeline in a process known as “pigging”.

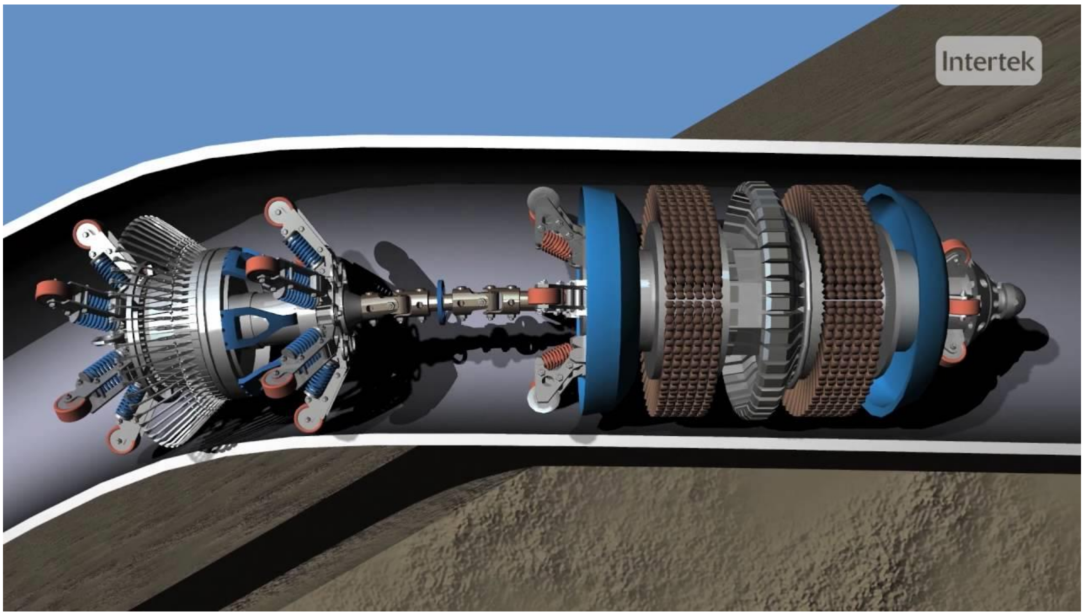


Figure A1.7 Intelligent pigging pipeline inspection diagram (Intertek, n.d.).

Mixing stations (intake) – these are where gas enters the network from company owner lateral lines from the various production facilities or at junctions between lines.

Compressor station – The gas network covers some considerable distances, along which the pressure will naturally drop. Compressor stations are strategically placed on the network to maintain pressure. These sites consist of either gas turbines, reciprocating engines or electric motor driven compressors, all of which are vulnerable to fine ash due to its corrosive and abrasive qualities.

Other components of gas stations may also include metering systems, odorization plants, coalescers and filters, gas chromatographs. Each site will uniquely contain a variety of the above-mentioned components. However, for this research, a simplified high-level view was taken. Identification and site-specific further research will be required, with prioritisation of assets in the PDC and Lahar risk zones, followed by implementation of risk reduction improvements at the earliest opportunity.

Figure A1.8 Above ground Pipeline assets - mixing/in-take point.

Interdependencies	Electricity and telecommunications are required, but non-essential to the operation of the main transmission pipeline if lost.
Hazard impacts:	Static Pressure (Structural loading) – This will vary between the individual assets, as they consist of a wide range of configurations of pipework with additional aspects. The surface area is likely too small in most cases to be a concern. Even burial, if it is not cemented, would be relatively easy to clean up without harming the integrity of the main buried pipeline. Temperature – From known operational temperature limits for pipelines, exposure to temperatures of above 45ºC for more than 15 mins will require reduced pressure and

inspections for stress fracturing as a minimum. These temperatures are likely to be exceeded by pyroclastic density currents and flows. Therefore, the small number of assets identified in the PDC risk zone should receive furthermore detailed risk assessment with any risk reduction changes implemented at the earliest opportunity.

Dynamic pressure – Where above ground assets occur close to rivers and streams, new lahar modelling would be beneficial to consider site-specific flood and lahar risks. Most above-ground assets are self-contained and can withstand a range of dynamic pressures. However, if exceeded, the above ground assets would be destroyed. However, this is unlikely to affect the main buried transmission pipelines, with redundancy already built into the pipeline network. One exception would be a sector collapse scenario when damage is likely to be catastrophic and analogous to landslides which have damaged the pipeline previously.

Ash concentration - Most above ground assets are self-contained and can withstand the range of tephra deposits. The main exception to this is the delivery and compressor stations where air-intake is a critical component of the equipment. Through air-intakes, ash causes abrasion, and associated filters become clogged. In these cases, further research is recommended, including drawing on experiences from previous central plateau eruptions when fine ash contamination compromised some of these asset types.

A1.3 Production Facilities – Type 3

These are the most complex of asset locations comprising many kilometres of pipeline, cooling and separating towers and storage as the hydrocarbon product is divided into components of water, gas, oil, condensate and prepared for transportation. They may be small satellite operations or much larger scale. They tend to comprise of multiple sub-processes and storage tanks, flares, office and control buildings, water pits for fire safety and have constant on-site supervision. Depending on scale and product type pipelines or road transport is used to deliver the product to end-users or storage facilities for export through Port Taranaki.

Onsite storage tanks are categorised as storage tanks, and therefore a single geographical location may have multiple asset types.

Figure A1.9 Mains power junction box.

Figure A1.10 Heat exchange tower with air intake value.

Figure A1.11 Close-up photo of an air intake on heat exchange showing the honeycomb filter.

Figure A1.12 Air intake for cooling compressor engines housed in soundproof unit (smaller production site).

Figure A1.13 Multiple air intakes for cooling systems on a larger production site.

Figure A1.14 Air intake for larger scale heat exchange units.

Figure A1.15 Photo showing the complex larger scale production facilities with many kms of pipeline, flare stack to the left distance and two cooling towers to the centre-right.

Figure A1.16 Further examples of air compressors at a larger production site that are vulnerable to air quality

Figure A1.17 Panoramic view of a larger production site with ongoing work showing a complex industrial workplace that sits within a zone that has high to intermediate risks of lahars and therefore sediment burial, dynamic pressure as well as ash fall hazards.

Figure A1.18 Complex electronics computer control unit that would be sensitive to fine ash damage note limited dust filter capacity on the doors of the cabinet.

Figure A1.19 Air compressor unit for the various pneumatic values around the production site. This unit is sensitive to the air quality and should be housed in a building with ash-lock doorways to reduce fine ash invasion.

Figure A1.20 Methanol control units, another example of equipment that is very sensitive to a fine ash and requires electricity to operate. If compromised, the whole site becomes impacted.

Interdependencies

Electricity, Water, road networks, pipeline integrity, fuel, transport (air, road & water), telecommunications.

Electricity – most production stations are entirely dependent on electricity to run. Some generate their electricity from gas turbines. However, these can easily be compromised by ash-fall.

Water – Production sites are required by Health & Safety regulation to have access to water for fire suppression. Some facilities store water in open pits or tanks (in the ground or above ground), and they can become contaminated by ash – causing water pumps to block and corrode rapidly.

Pipeline integrity – Where production facilities output dry gas that feeds into the national gas network, the integrity of the pipeline to the mixing station and beyond are essential. However, some smaller facilities may be able to flare the gas for a limited period and maintain production where the remaining product is transported via the road networks.

Road networks – all facilities are manned. Therefore, staff will need to access the site via road to enable the site to operate. Additionally, some product and consumable are transported by road to and from the site. Many sites rely on contractors and their equipment which also depend on the road networks.

Other Transport - for some offshore facilities helicopter access is essential for staff and consumables. If the airspace around the facilities is shut down due to ash-fall, this will impact operations. For exporting of material and importing of fuel and equipment, Port Taranaki has become pivotal. If the port had to close due to sedimentation or ash fall, this would impact sites in several ways from a lack of fuel, storage capacity at Tank farms reaching its maximum limits or no fuel arriving creating shortages.

Telecommunications – some site are critically dependant on communications, from monitoring various components around a site to monitoring satellite or remote wells and facilities. Without these for prolonged periods, risks increase beyond an acceptable level, requiring production to cease until the communication blackouts are resolved.

Hazard impacts:

Note – due to the variation in these sites further site-specific research is required to take a focused component level assessment. Impacts here are generalised.

Static Pressure (Structural loading) – Some sites with flat-roofed buildings or large span roofs may become compromised with heavier ash fall, especially if it becomes wet. Other aspects may not be easily restorable if buried in cemented ash.

Temperature – for sites in Zone A, in addition to the pipeline integrity issues caused by temperatures, sites with explosive material still present at the time of impact would pose a large risk to the temperature ranges present in pyroclastic density currents and flows. Where sites sit in the PDC risk zones proactive evacuation, shut down and purging of the product should be considered alongside further site-specific research.

Dynamic pressure – site inundations of lahars, debris flow or PDCs are likely to cause substantial damage given the complex and sensitive nature of this asset type. Where assets are within lahar risk zones further site-specific research is recommended, with the implementation of risk reduction options to minimise damage and allow a more rapid recovery at the earliest opportunity. Examples of lahar risk reduction implemented following the 1990 Mt Redoubt eruption at the Drift River terminal, Alaska includes: a dyke and levee concrete bund helped mitigate damage during the 2009 Mt Redoubt eruption and lahar.

Ash concentration – As shown the photographs there are many air drawing components on production sites. Additionally, sites are also critically reliant on water for fire suppression which may be stored in open pits or tanks on site or drawn from nearby streams or rivers, which are very sensitive to finer the ash. Abrasion qualities of ash can damage moving parts and larger ash particles can block, suffocate or trip the range of equipment that is reliant on clean air or water quality. Therefore, any sedimentation in rivers or streams, atmospheric air quality reduction or remobilised ash will pose hazard impacts.

For sites in Zone A, larger tephra may present ballistic type damage to the assets. However, further research at a site and component level will provide more in-depth insight into the risks and methods of risk mitigation.

A1.4 STORAGE TANKS – TYPE 4

Storage tanks used by the petroleum sector come in a wide variety of shapes, sizes, materials, roof types and contain a range of liquid products from oil, LPG, naphtha, clean water and wastewater. These can be divided into two broad categories; fixed and floating roof tanks. Under each category, several roof construction types exist along with variations in materials and foundations.

Some tanks store the various products including both clean and wastewater. Clean water required for safe operations for emergencies and fire suppression is stored in open pits or tanks. Product and waste water tanks are all closed tanks, either upright tanks or storage bullets with a variety of fixed or floating roofs.

Risks for clean water tanks come from ash fall which causes water turbidity and water pumps to fail through blockage or rapid corrosion of elements.

Some work has been undertaken that considers the ash fall weights required to capsize a floating roof tank for a Mt Vesuvius eruption (Milazzo et al., 2013). However, the Taranaki regions higher rainfall compared to Italy will require further evaluation when undertaking more detailed site-specific studies.

Figure A1.21 Omata Tank Farm near Port Taranaki (14 tanks in total).

Figure A1.22 Fixed roof storage tanks at Port Taranaki.

Additional risks peculiar to the Taranaki region are for oil storage tanks – due to the high wax content of Taranaki oils, even after blending to the "McKee blend" standard, loss of mains power to retain heat and circulate the oils for a prolonged period could result in the oil becoming solid. Further research recommended for the wide range of tanks.

Figure A1.23 Paritutu Tank Farm near Port Taranaki (five condensate floating roof storage tanks).

Figure A1.24 Onsite closed lid small water storage tank.

Figure A1.25 Large onsite water storage tank - open top.

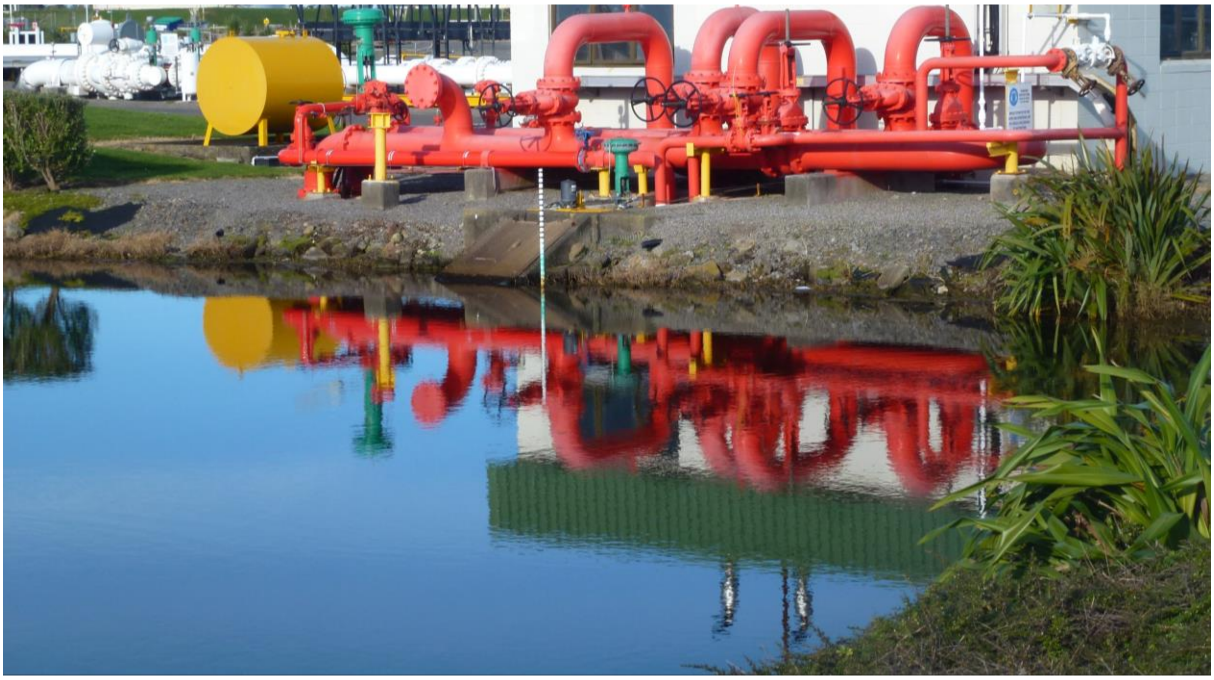


Figure A1.26 Onsite open, clean water storage tanks required for fire suppression.

Figure A1.27 Smaller open, clean water storage tanks for fire suppression.

Figure A1.28 Small production site close roof storage tanks.

Figure A1.29 Large production site floating roof storage tanks.

Figure A1.30 Production site waste-water tank and oil/condensate storage horizontal tanks.

Interdependencies	Electricity to operate pumps, valves and heating and circulating oil through the system.
Hazard impacts:	Static Pressure (Structural loading) – There is a wide variation in the types and sizes of storage tanks on the tank farms and those on production or well injection sites. Further research is required to consider the structural loading risks for the distinct types. However, some work on floating roof storage tanks exists from Italy. Studies have shown that significant levels of ash-fall would be required to cause floating roofs to capsize (Milazzo et al., 2013; Milazzo et al., 2012). To mitigate capsize risk reduction of ash-fall build up and rain complications, regular cleaning of roofs will be required. Temperature – where assets of this type are in Zone A, further site-specific research is required to understand the risks to the tanks and connecting pipelines and valves to PDC temperatures. The impacts may include combustion of the product, melting of tank walls or valves. Dynamic pressure – Where sites are in sector collapse, lahar or PDC zones they will be at risk from integrity failure by the characteristics of those hazards. Therefore, pre-emptive purging of tanks pre-eruption could be considered depending on the sites location and risk profile. Note lahars from the 2015 Calbuco Volcano, Chile displaced LPG tanks containing product from a small industrial site downstream, which remained intact and was able to be safely recovered (Dussaillant et al., 2016). Further site and component-specific research will help inform more detailed risk assessment and risk mitigation options. Ash concentration - ash fall will compromise open water storage tanks by blocking water pumps and causing rapid corrosion damage. For oil storage dependant on circulation and heating, ash fall is likely to disrupt power supply creating risk. Further research is required to consider the impacts of oil storage subjected to long-term loss of heating and circulation.

A1.5 BUILDINGS – TYPE 5

Buildings for the petroleum industry range from the structurally designed office buildings in New Plymouth to small porta cabins or converted shipping container units. Some of the onsite control buildings use the more temporary building types, which is a large vulnerability for the industry as these contain important electrical wiring and computers as well as the staff. Many of the onsite control buildings do not have adequate ash lock porches and have filters or air vents that could be easily compromised by ashfall. This is an immediate area for improvement for the sector.

Below are some of the different building type examples.

Figure A1.31 Onsite accommodation and welfare support structures.

Figure A1.32 Converted storage tank control room.

Figure A1.33 Office buildings (from Google Street View).

Interdependencies	Electricity, telecommunications, water, air quality
Hazard impacts:	Existing building asset types and fragility functions exist within RiskScape. Therefore, this asset type has not had a vulnerability model developed. However, a few relevant comments below are worth making for this sector. Static pressure & ash concentration – ashfall penetration can compromise contents, especially electrical and computers. For more temporary buildings the ashfall may also cause static loading damage. Temperature – if wooden or temporary structure is exposed to very high temperatures this may cause combustion depending on the material. Dynamic pressure – for the temporary buildings or onsite buildings, these may not have solid or robust foundations or fixings to foundations, resulting in the displacement of the entire building.

A1.6 INDUSTRIAL USERS – TYPE 6

A variety of end-users exist around the Taranaki region, some take product directly from the production facilities and located close to the relevant production sites. End users may be Methanol plants, LPG bottling stations, dairy processing or fertiliser factories that rely on the various products. Other entities that are considered end users are Port Taranaki who handles the import and export of various products and equipment that the sector relies on and manages water-based transportation docking.

Interdependencies	Not considered in this research – further site-specific studies are recommended. However large-scale gas users are subject to the Gas Governance (Critical Contingency Management) Regulations 2008 if supplies become disrupted. Further research into the symbiotic relationships between some production sites and end users for risk planning is recommended.
Hazard impacts:	Not considered in this research – further site-specific studies are recommended.

A2.0 APPENDIX B – EXERCISE PAHU

Taranaki CDEM group developed exercise Pahu in conjunction with the Natural Hazard Platform partners of Massey University and GNS Science. The exercise was previously run as Exercise Billow in 2008 and developed further for Exercise Pahu in 2013. Based on the Tahurangi scenario, small-scale eruption with an associated lava dome collapse event producing a small localised debris avalanche down existing drainage channels to the Northwest side of the volcano, new lava, small volumes of tephra and ash, and lahars to the Northeast and Southeast (Cronin, 2012). This scenario was developed based on research that includes the Tahurangi eruption episode deposits dated between ~AD1644 and ~AD1755 (Zernack et al., 2011). The research concludes that this is the most common known event to occur in the Mt. Taranaki eruption sequence (Platz et al., 2012; Procter et al., 2010; Turner, Cronin, Bebbington, et al., 2008; Turner, Cronin, Smith, et al., 2008). This exercise uses the current topography, and it does not cover the full range of eruption sizes and hazard directions that have been known to be produced by Mt. Taranaki in the geological history. Likewise, it represents a small-scale eruption in comparison to analogue volcanic eruptions from around the globe such as Calbuco volcano, Chile, 2015, Mt. Redoubt, Alaska 1989 and 2009, or Mt. St. Helens, USA, 1980.

Exercise Pahu was developed to test the Taranaki Civil Defence Emergency Management Group's response to a volcanic event. It involved multiple CDEM groups, agencies and lifeline organisations. Two phases were used, the first being the leadup which is timed to occur over a 19-day period culminating in the first small eruption. Phase two moves through a single day on the 20 November, where all agencies were tested in real time with various injects throughout the day.

The exercise objectives were as follows:

- Objective 1 – To ensure there is a state of readiness for Taranaki CDEM Group.
- Objective 2 - To demonstrate EOC procedures.
- Objective 3 - To demonstrate reporting arrangements.
- Objective 4 - To demonstrate relevant Advisory/ Coordination Group arrangements.
- Objective 5 - To demonstrate decision-making arrangements in the CDEM Group EOC.
- Objective 6 - To test communications.
- Objective 7 - To demonstrate Public Information Management (PIM) systems and processes.

The high-level scenario timeline, taken from the scenario planning documentation, was as follows:

November 1-5:

An increase in seismic activity recorded by Geonet in the Taranaki region, consisting of irregular swarms of moderate (felt) earthquakes and aftershocks along the Cape Egmont Fault Line and a few small deeper events under the volcano.

November 5-11:

There have been continuing and increasingly shallower earthquakes under the volcano. These initial signs indicate that the volcanic unrest is developing into a volcanic crisis where the possibility of eruption is likely. The public is aware as many have felt the continuing earthquakes and aftershocks. The occurrence of seismic activity under the volcano triggers a change in the Volcanic Alert Level for reawakening volcanoes; raised to Level 1. Evacuation of the Egmont National Park is implemented, due to GNS reporting and change in Volcanic Alert Level to Level 1.

November 11-14:

Increasingly shallower earthquakes under the volcano are continuing. Ground deformation appears on the cone, with fissures (large cracks) reported. These initial signs indicate the volcanic unrest is developing into a volcanic crisis where the possibility of eruption is likely. GNS in briefings to the Taranaki CDEM Group, attribute this to the intrusion of new magma (molten rock) into the base of the volcano and movement of magma outward into the conduit system in the cone.

November 14-16:

Continuing and increasingly shallower earthquakes under the volcano are ongoing. Ground deformation continues to develop. These signs indicate that the volcanic unrest is developing, and the possibility of an eruption is very likely. Volcanic Alert Level for reawakening volcanoes raised to Level 2.

November 17-19:

Volcanic unrest develops into small eruptions starting near the summit of the volcano, being driven by steam. The continued increase in seismic activity and the minor volcanic activity promotes a further change in the Volcanic Alert Level to Volcanic Alert Level 3. Light ash-falls are being experienced to the northeast (due to a south-westerly wind), even as far north as the Waikato region. The occurrence of a large landslide into the (Hangatahua) Stony River has happened on the northwest slope of the volcano due to the increased earthquake activity and recent heavy rain.

19 November:

Eruptions are continuing near the summit and may be increasing in vigour. Debris flows are being reported on the northern slopes of the volcano.

20 November:

The main eruption at 2am with shock waves rattling buildings within 2kms of the vent and an ash plume that reaches > 10km above the surface. Two large lahars effect two main rivers in the area, one to the northeast and the second to the South, with other rivers and streams impacted by ash-fall and smaller lahars affecting the water quality. Reports of 15 mm of ash fall on State Highway 3 between Inglewood, Stratford and Manaia, with ash fall of up to 10 mm occurring up to 50 km downwind of the volcano.

From the exercise results and interagency collaboration, a Taranaki volcanic unrest plan was developed in 2015.

For exercise Pahu or Mt. Taranaki in general, no GIS map of the hazards exists. However, for this project, a two-phase scenario was developed.

The phases can be used as standalone eruptions, or as labelled a larger two-phase eruption with a small phase 1 and larger phase 2 (**Figure 2.5** and **Figure 2.6**).

For both eruptions, the relevant QMAP formations were selected and edited to remove isolated (likely remobilised) deposits and used one of the lahar deposits as a plume collapse PDC for the scenario. This assumed that plume collapse PDCs are not always captured well in the geological record, due to being reworked and eroded by rain, and then categorised as lahar deposits in the geological record.

To collate eruptions to stratigraphic names of relevant formations, Zernack et al. (2011) was referenced.

The small eruption is based on the Tahurangi eruption using the Hangatahua Formation and Peter's lavas. Plus, a low/medium eruption forecast of 18 September at 1800.

The large eruption is based on the Kahui eruption using the Kahui formation and Warwick lavas. Plus, a high/large eruption forecast of 19 September at 0600.

In some cases, an artistic licence was taken to modify the shapefiles to extended them back to the vent or out a little further to reach petroleum assets.

A3.0 APPENDIX C – LEGISLATION AND REGULATIONS

Table A3 1 Table of Petroleum related legislation in New Zealand.

Legislation/Regulation	Category	Responsible Agency (Legislative/Operational)
Health and Safety at Work Act 2015	Health & Safety	MBIE/WorkSafe
Health and Safety in Employment (Pipelines) Regulations 1999	Health & Safety	MBIE/WorkSafe
Health and Safety at Work (Petroleum Exploration and Extraction) Regulations 2016	Health & Safety	MBIE/WorkSafe
Workplace Exposure Standards and Biological Exposure Indices 2016	Health & Safety	MBIE/WorkSafe/TRC
Health and Safety at Work (Hazardous Substances) Regulations 2017	Health & Safety	MBIW/WorkSafe
Crown Minerals Act 1991	Mineral rights	MBIE/New Zealand Petroleum & Minerals
Crown Minerals (Petroleum) Regulations 2007	Mineral rights	MBIE/New Zealand Petroleum & Minerals
Gas Act 1992	Operational	MBIE/WorkSafe/Gas Industry Co
Gas Governance (Critical Contingency Management) Regulations 2008	Emergency Management	MBIE/CCO
Gas (Safety and Measurement) Regulations 2010	Operational/Health & Safety	MBIE/Gas Industry Co
Plumbers, Gasfitters, and Drainlayers Act 2006	Operational	MBIE/Gas Industry Co
Civil Defence Emergency Management Act 2002	Emergency Management	MCDEM/Councils
National Civil Defence Emergency Management Plan	Emergency Management	MCDEM/Councils
Resource Management Act 1991	Environmental	MfE/Councils
Environmental Protection Authority Act 2011	Environmental	MfE/EPA
Hazardous Substances and New Organisms Act 1996	Environmental	MfE/EPA
Maritime Transport Act 1994	Environmental/operational	MfT/Maritime NZ
Standards and Accreditation Act 2015	Construction and design	MBIE/Standards NZ
AS/NZS ISO 31000:2009 Risk management - Principles and guidelines	Emergency Management	MBIE/Standards NZ
AS/NZS 2885:2016 Pipelines - Gas and liquid petroleum (Parts 1-5)	Construction and design	MBIE/Standards NZ
NZS 5435:1996 Specification for liquefied petroleum gas (LPG)	Construction and design/operational	MBIE/Standards NZ
NZS 5223:1987 Code of practice for high pressure gas and petroleum liquids pipelines	Construction and design	MBIE/Standards NZ
AS/NZS 4130:2009 Polyethylene (PE) pipes for pressure applications	Construction and design	MBIE/Standards NZ
BS 6843-3:1988 Classification of petroleum fuels. Liquefied petroleum gases	Construction and design/operational	MBIE/Standards NZ
BS ISO 12917:2017 Petroleum and liquid petroleum products. Calibration of horizontal cylindrical tanks.	Construction and design	MBIE/Standards NZ

A3.1 Notes on the AS/NZS and API Standards

AS/NZS 1170.0 – General principles (Standards New Zealand, 2002a, 2002b). This sets out the design probabilities for the buildings against snow, wind and earthquake events, which varies based on the design working life, importance, and if cyclonic wind considerations are required. It is unclear what design life and importance (risk of exceedance of design load) each of the various asset categories is built to without further detailed studies.

AS/NZS 1170.2 – Wind (Standards New Zealand, 2011). This design standard is for onshore assets only, with regional variation for the research area of Taranaki (region A7) requiring a 'Lee multiplier' for South-east wind. Additional complexities include regional gust wind speeds, wind direction multipliers, site exposure multipliers, i.e. Terrain/height, shielding and topographic multipliers such as internal and external pressure coefficients. All of which vary location to location and are applied based on the building design. The code does not specifically consider volcanic hazards. However, there is an additional consideration of impact loading from windborne debris that can be applied. It is unsure if any structures in this research have been built with this factored.

AS/NZS 1170.3 – Snow and ice (Standards New Zealand, 2003a, 2003b). Petroleum assets in the Taranaki region straddle two snow design regions, one which is a sub-alpine classification. It is noted that the snow loading design standards do not cover vulnerability to avalanche, avalanche blast, landslides, or increased load due to rain falling on snow. Additionally, the building location, design and materials play a large factor in determining the value, giving each building or asset an individual value that has not been determined by this research.

API 650 - Welded Steel Tanks for Oil Storage Twelfth edition (American Petroleum Institute, 2013). This is the American Petroleum institute's standard for petroleum storage tank designs, while not NZ specific is an industry standard. Concern was raised about the earlier tenth edition of this standard having limitations around the maximum wind speeds (100 mph) and not accounting for snow loading which was revised for edition eleven (Kissell & Myers, 2003). However, the most recent standard (2013) has larger load limits and wind strength designs; it is unknown if older tanks are required to be retrofitted to the newer standards. Additional standards may also apply (API 620 and API 12D) depending on individual tank design and purpose.

API 6A - Specification for Wellhead and Christmas Tree Equipment. This sets out the distinctive design specification for wells for the industry, which includes minimum internal pressure thresholds.

A4.0 APPENDIX D – EXAMPLES OF ASH FALL DISTRIBUTION FORECASTS

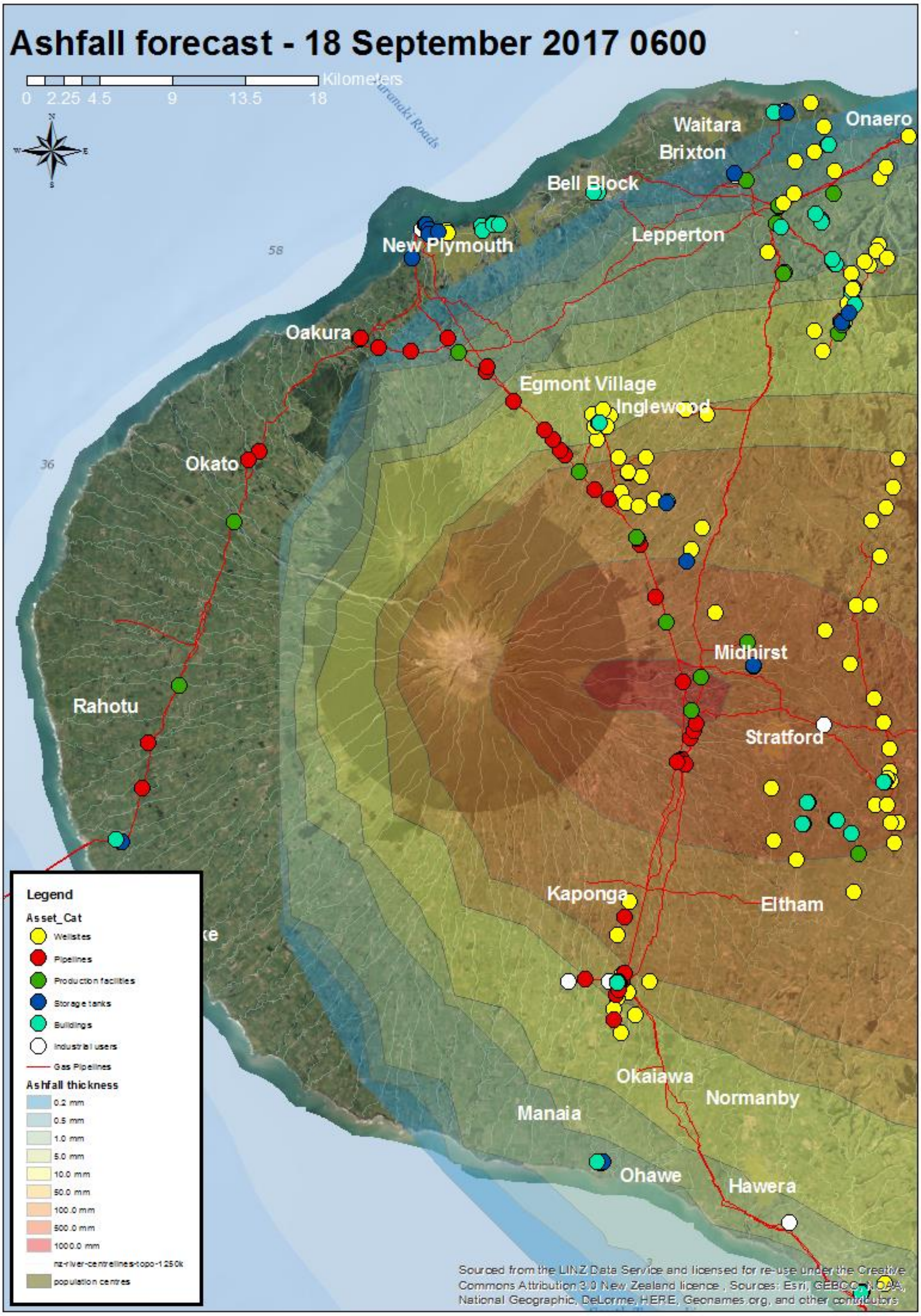


Figure A4.1 Large eruption height (15 km), small volume (0.01 km3) 0600 18 September 2017

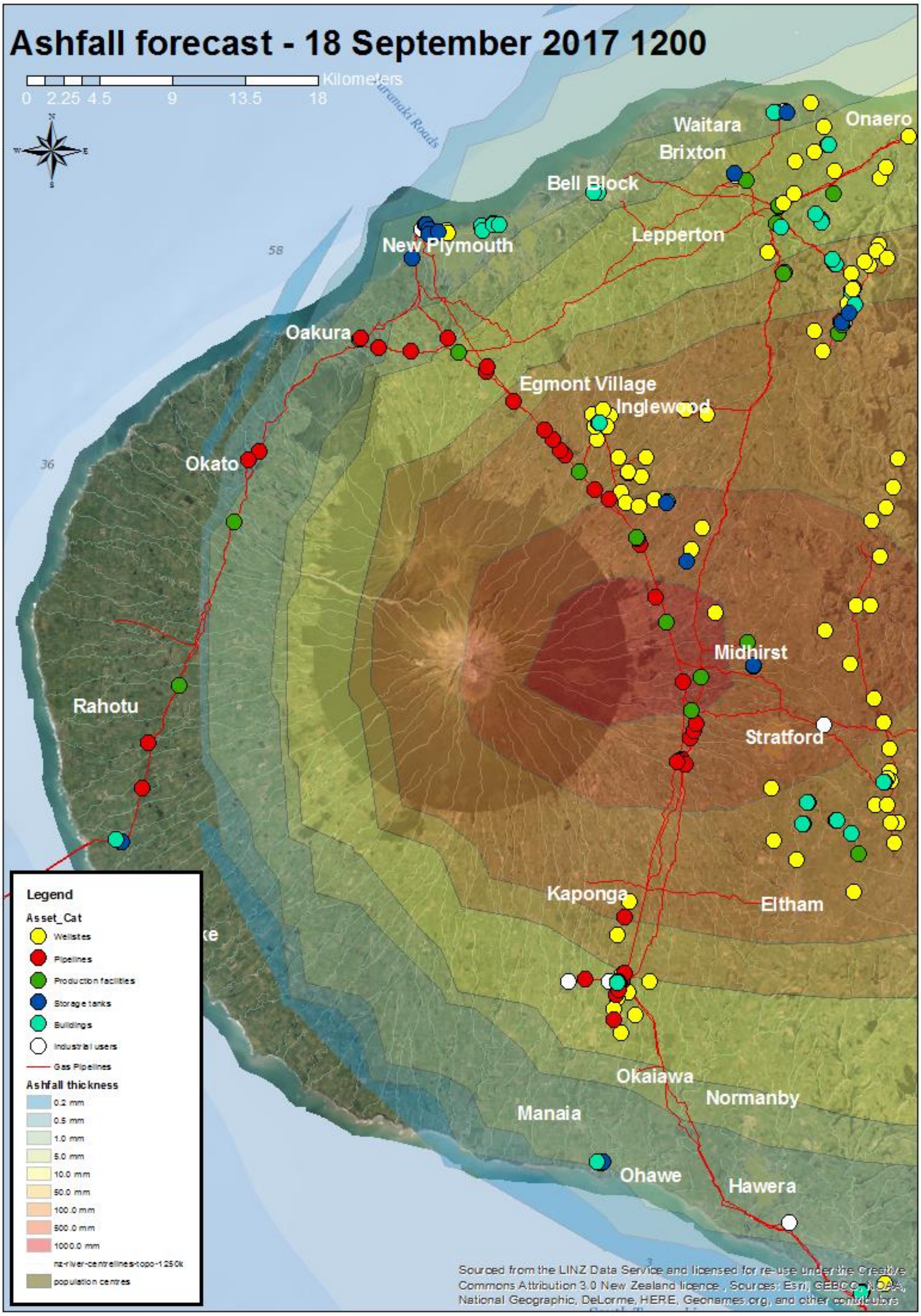


Figure A4.2 Large eruption height (15 km), small volume (0.01 km3) 1200 18 September 2017

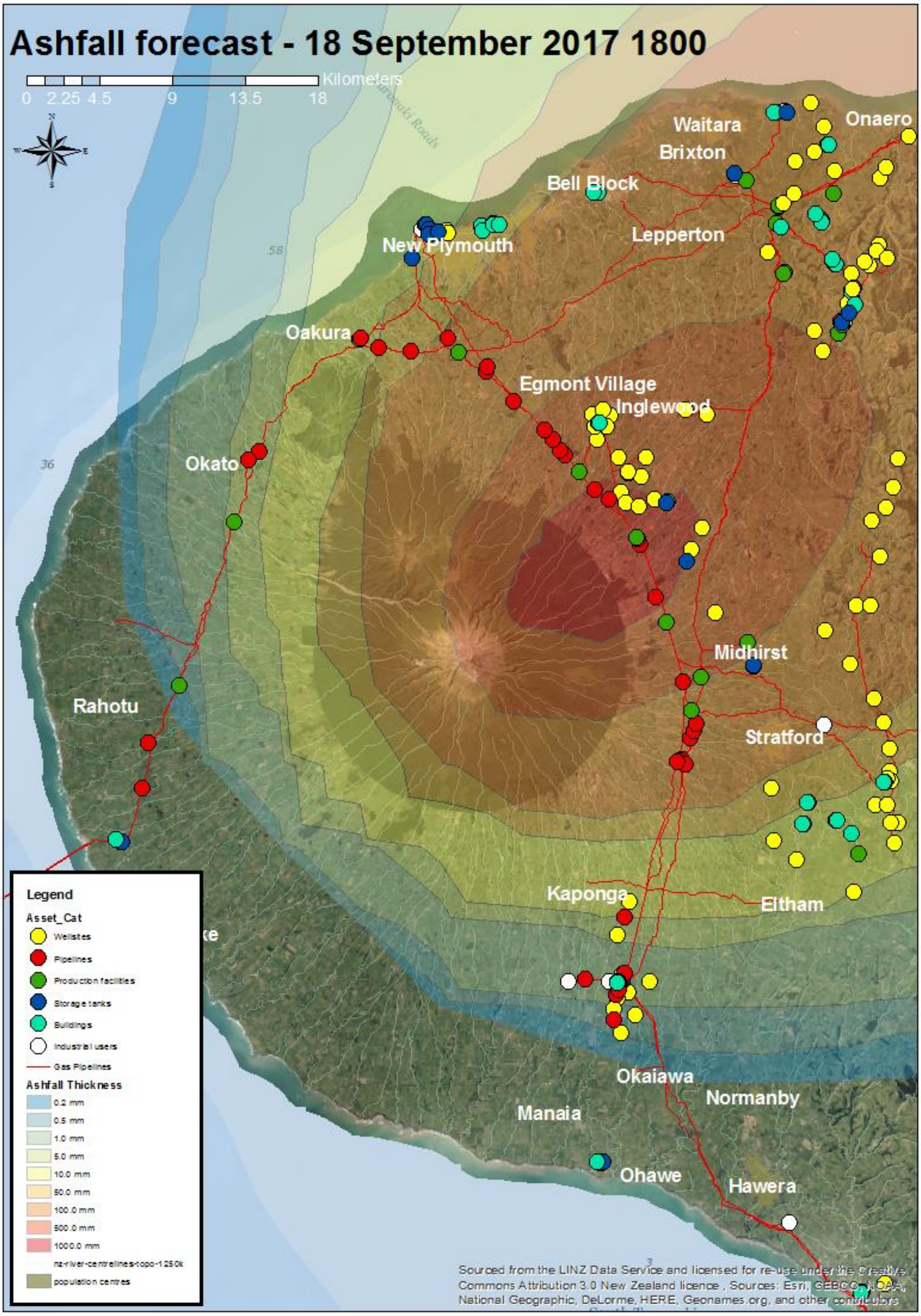


Figure A4.3 Large eruption height (15 km), small volume (0.01 km3) 18:00 18 September 2017

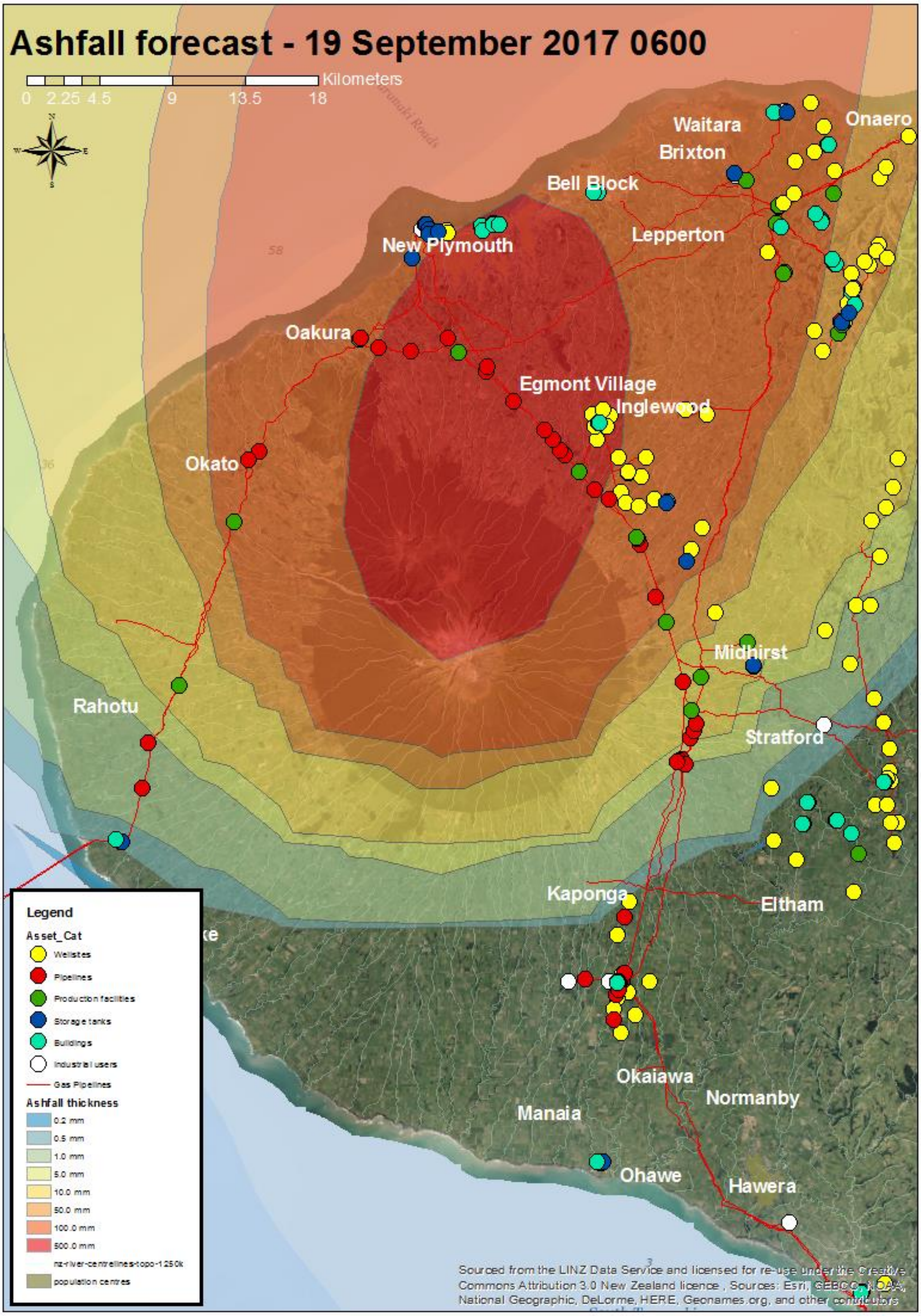


Figure A4.4 Large eruption height (15 km), small volume (0.01 km3) 06:00 19 September 2017

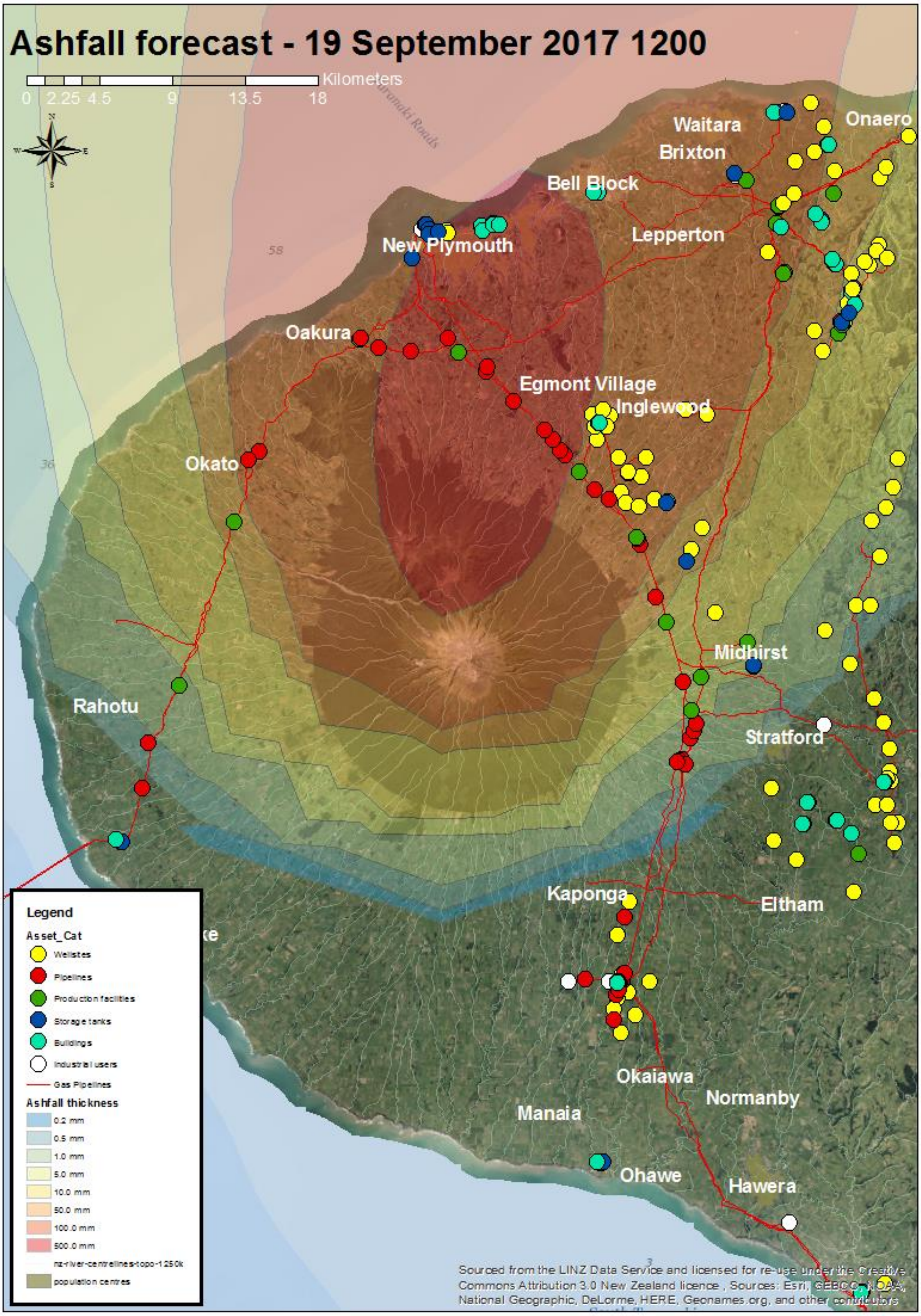


Figure A4.5 Large eruption height (15 km), small volume (0.01 km3) 12:00 19 September 2017

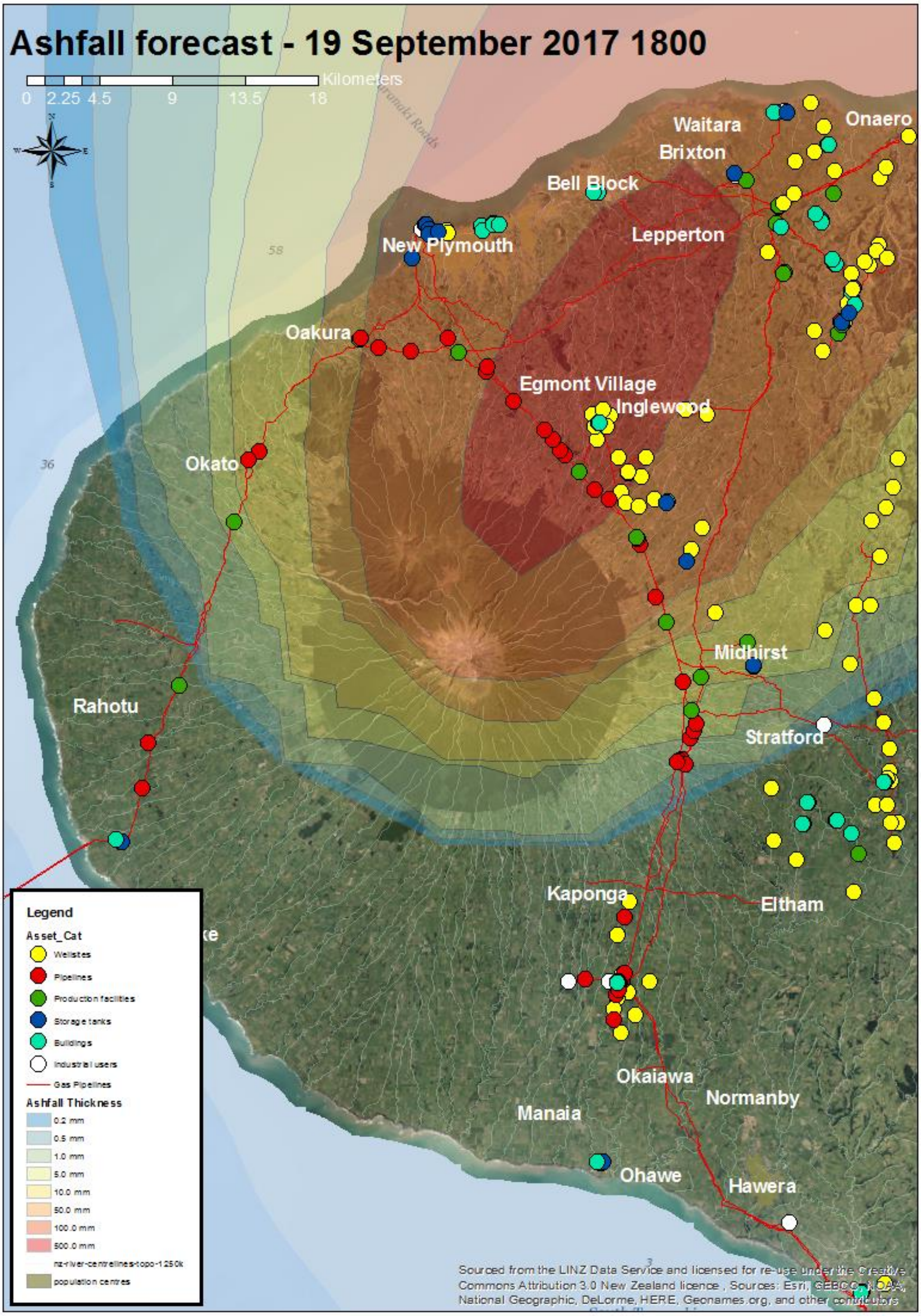


Figure A4.6 Large eruption height (15 km), large volume (1km3) 18:00 19 September 2017

A5.0 APPENDIX E – EXPERT ELICITATION WORKSHOP

As the main part of the thesis, discussion and consultation were required with the petroleum industry. Some companies agreed to collaborate by sharing data, information and organising site visits in addition to attending the expert elicitation workshop. A wider group of industry representatives, regulators, civil defence and local and regional council staff, were invited to an expert elicitation workshop facilitated by myself, seven months into the research timeframe. The workshop required careful and meticulous planning to ensure the key aims were identified and the outcomes achieved.

The rational aims of this workshop were to:

- derive the generic categorisation of the various petroleum assets locations in the region
- define the damage impact states and threshold categories
- prioritise interdependencies of the various asset categories.

The experiential aims of the workshop were to:

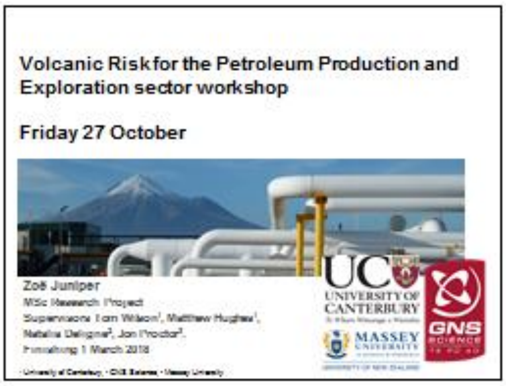
- ensure all attendees felt their expertise was valuable to the discussions while gaining knowledge of the importance and relevance of lifeline security
- strengthen understanding and relationships between the various attendees, specifically the civil defence team and petroleum industry
- produce a favourable impression of the work, so future research, publications and collaborations are achievable
- ensure a sense of ownership in the industry of volcanic hazard risk mitigation and a desire to continue the conversation internally, sector-wide and with civil defence.

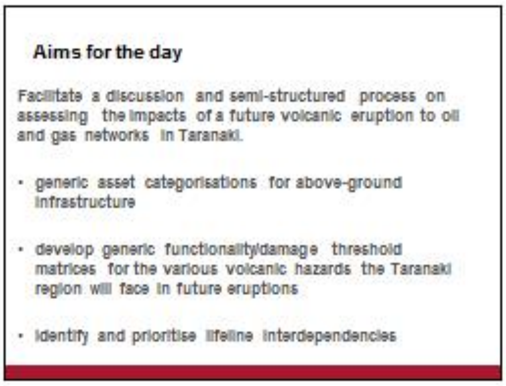
The workshop was held in Stratford and hosted by the Regional Council. In preparation for the workshop, a straw-man was compiled of suggestion of asset categories and provisional damage states from previous discussions and literature research. These were then tested during the workshop and revised based on discussions and feedback captured. The initial literature review and revisions following feedback from the workshop are discussed in the relevant sections.

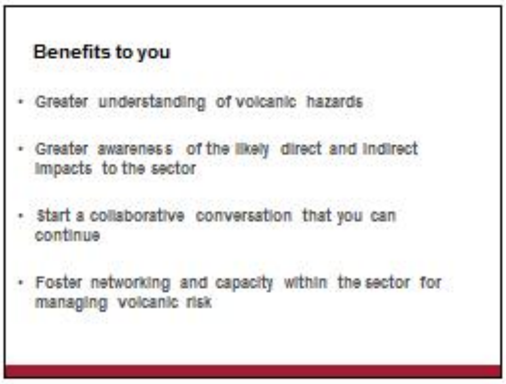
A5.1 AGENDA

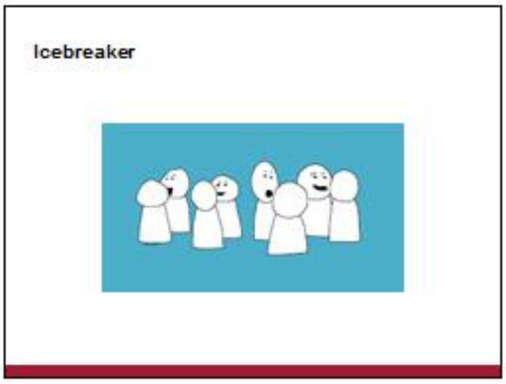
- Introductions & icebreaker
- Aims and overview of the research
- What are Mt. Taranaki's hazards?
- How to assess the damage from these hazards?
- Step 1 – classification of Taranaki's petroleum asset types
- Morning tea
- Step 2 – Thresholds for damage
- Step 3 – What are the operational dependencies for this industry?
- Wrap up
- Lunch

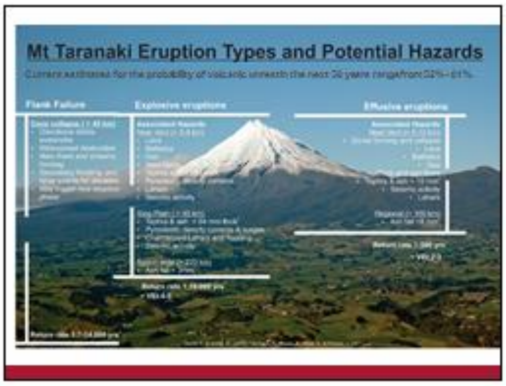
A5.2 PRESENTATION SLIDES

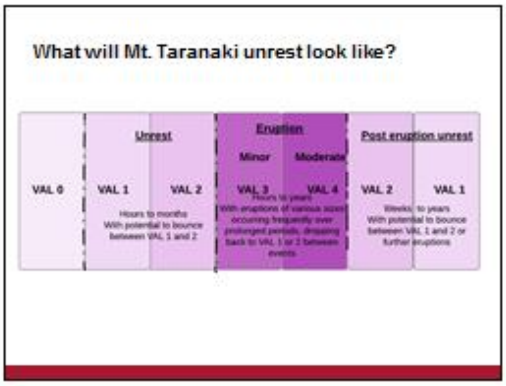








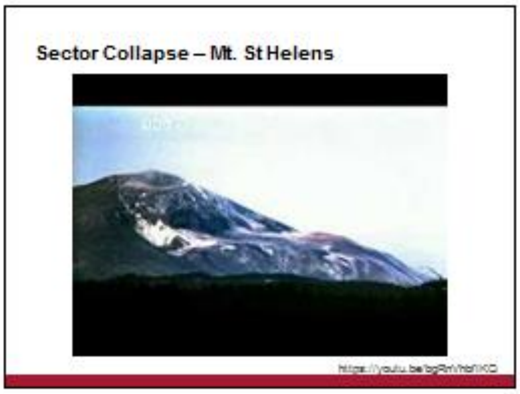


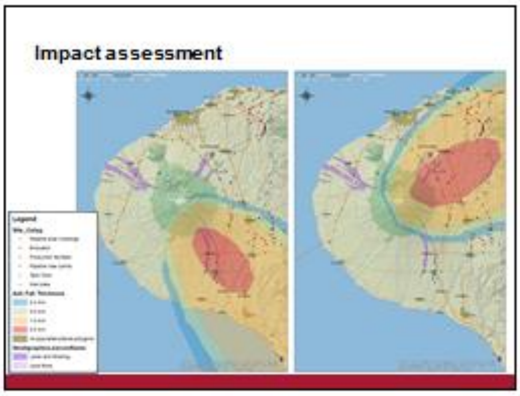


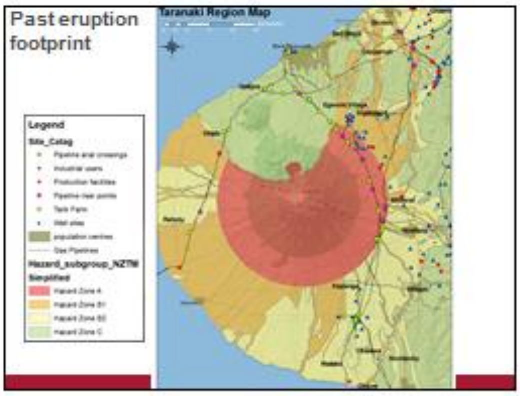

Pyroclastic density currents and flows

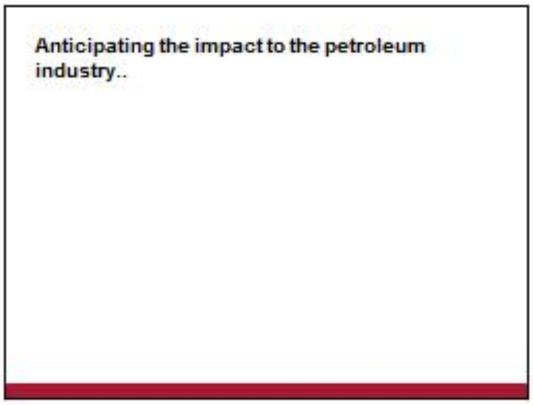

Lahars


Ashfall

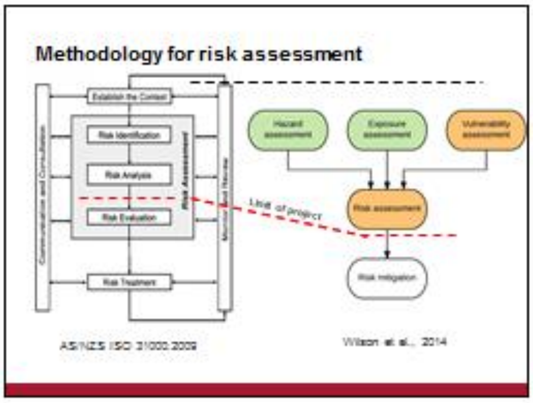

Sector Collapse – Mt. St Helens

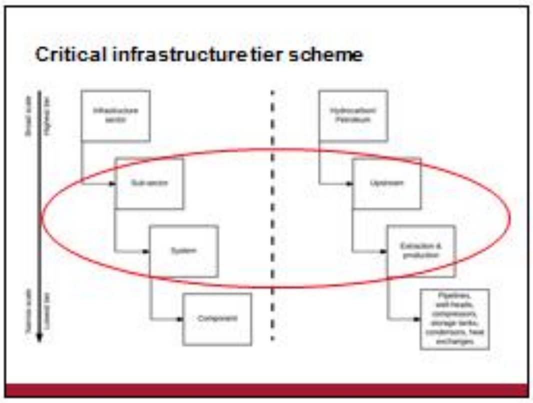

Impact assessment
Legend

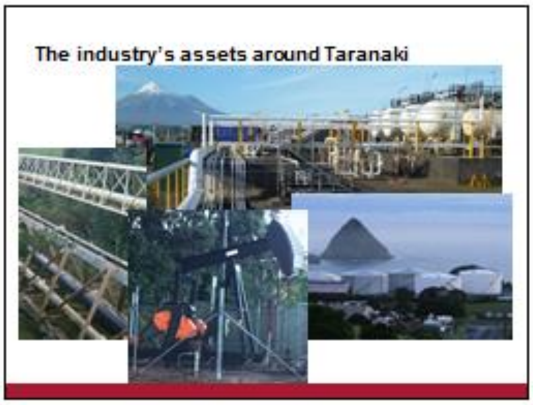

Past eruption footprint
Taranaki Region Map
Legend
Site_Catag
population centres
Gas Pipelines
Hazard_subgroup_NZTM
Simplified
Hazard Zone A
Hazard Zone B1
Hazard Zone B2
Hazard Zone C


Anticipating the impact to the petroleum industry..


Previous sector disruption in NZ
Maui Pipeline disruption 2011
September 2017
Upstream Industry
Midstream Industry
Downstream Industry


Methodology for risk assessment
Establish the Context
Risk Identification
Risk Analysis
Risk Evaluation
Risk Treatment
Risk Assessment
Communication and Consultation
Monitoring and Review
Hazard assessment
Exposure assessment
Vulnerability assessment
Limit of project
Risk assessment
Risk mitigation
AS/NZS ISO 31000:2009
Wilson et al., 2014

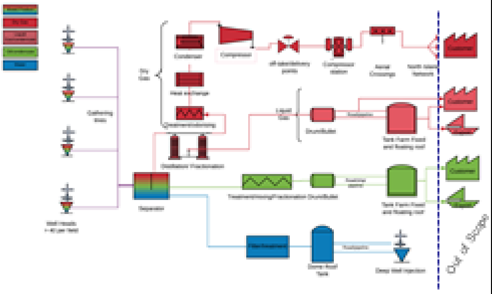

Critical infrastructure tier scheme
Infrastructure sector
Sub-sector
System
Component
Hydrocarbon/ Petroleum
Upstream
Extraction & production
Pipelines, well-heads, compressors, storage tanks, condensers, heat exchangers


The industry's assets around Taranaki


Measuring damage - Physical damage matrix
Understanding what damage states and hazard intensity thresholds are applicable for this industry and their assets.
No Damage
?
Minor Damage
?
Heavy Damage
Zero
Hazard intensity
Working matrix for the petroleum industry

 Zoë Juniper

Generic petroleum system map



Exercise 1

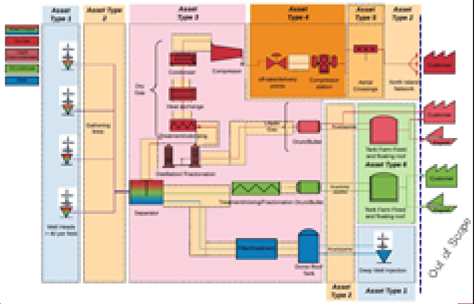
Aim: Identify asset categories that can be later used to develop category-specific damage threshold matrices.

In your groups:

1. (5 mins) Discuss: What are logical asset categories? Key: common function.
2. (When instructed) Improve Zoe's strawman or devise your own.
3. (Last step, on provided A3 template) Write list of asset categories and describe each category

Suggestion: asset managers / engineers take the lead, other group members support and question.
Requirement: generic and broad enough to cover entire NZ-based industry

Generic petroleum system map



Proposed asset categorisation

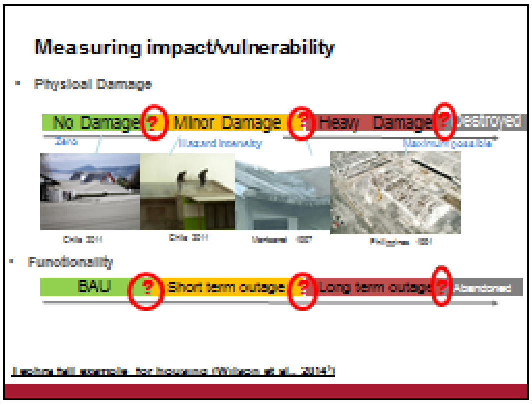
Category	Description
Wellsite	[illegible]
Special Pipeline crossing	[illegible]
Pipeline Substation	[illegible]
Underground pipelines	[illegible]
Product terminations	[illegible]
Storage Tank Farms	[illegible]
End Users	[illegible]

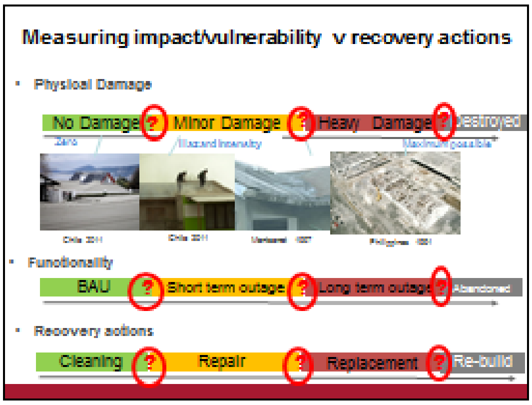
Does this work in a generic sense for the upstream industry?

Morning tea

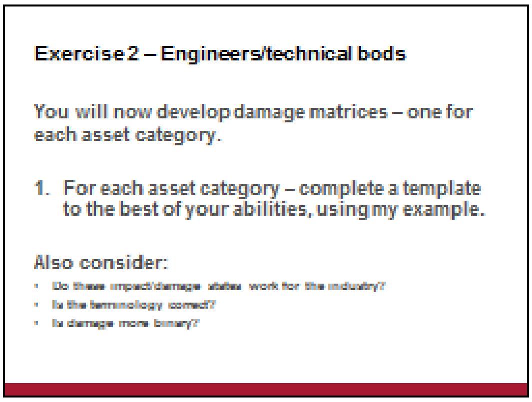
Methodology for risk assessment

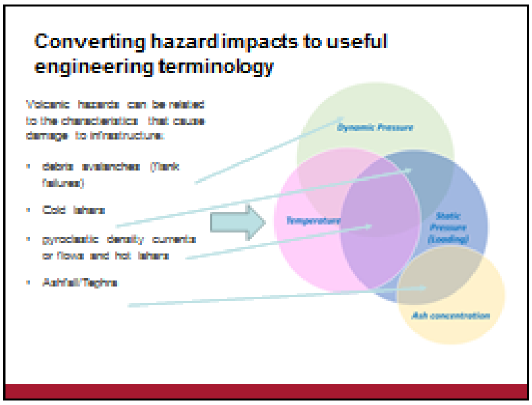
Wilson et al., 2014

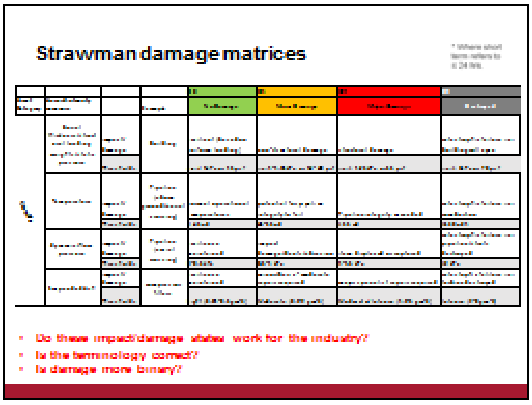

Measuring impact/vulnerability
Physical Damage
No Damage
Minor Damage
Heavy Damage
Destroyed
Zero
Hazard Intensity
Maximum possible
Functionality
BAU
Short term outage
Long term outage
Abandoned
Tephra fall example for housing (Wilson et al., 2014)


Measuring impact/vulnerability v recovery actions
Physical Damage
No Damage
Minor Damage
Heavy Damage
Destroyed
Zero
Hazard Intensity
Maximum possible
Functionality
BAU
Short term outage
Long term outage
Abandoned
Recovery actions
Cleaning
Repair
Replacement
Re-build


Exercise 2
Group 1
Engineers & technical bods
Group 2
HSE managers/policy
(non engineers)


Exercise 2 – Engineers/technical bods
You will now develop damage matrices – one for each asset category.
1. For each asset category – complete a template to the best of your abilities, using my example.
Also consider:
Do these impact/damage states work for the industry?
Is the terminology correct?
Is damage more binary?


Converting hazard impacts to useful engineering terminology
Volcanic hazards can be related to the characteristics that cause damage to infrastructure.
debris avalanches (flank failures)
Cold lahars
pyroclastic density currents or flows and hot lahars
Ashfall/Tephra
Dynamic Pressure
Temperature
Static Pressure (Loading)
Ash concentration


Strawman damage matrices
Do these impact/damage states work for the industry?
Is the terminology correct?
Is damage more binary?

Exercise 2 – others

You will discuss functionality and things the differ assets depend on to work and when these start to be impacted by the unrest scenario.

Part 1

1. Discuss what the different dependencies are for the petroleum sector. Write one per post it not and stick across the top of the flip chart – see strawman.
2. For each discuss what levels of dependency exist. i.e. critical/not required etc.
3. For each asset category – decide what level of dependency and colour chart. – add 1,2,3 in terms of importance.

Strawman interdependency matrix (critical lifelines only)

Asset types dependencies on ...	Electricity	Dry Gas	Road Fuel	Coms	Pipeline Integrity	Transport networks (Air/port/road)	Human Resources	Water / Wastewater
well sites								
production facilities								
Pipelines								
Transportation								
Storage								

What is missing and what are the priorities?
What non critical lifeline things will cause loss of functionality?

Exercise – the others

Part 2

Considering the unrest stages – when will the different dependencies start to impact functionality of the different assets ?

Mark key decision/disruption points on A3 timeline using post it notes

- When does HSE come into play?
- When do internal policies kick in?
- What impact will self – evacuation and formal evacuation zones have?
- How long can you maintain lower or stopped production?
- What is required to start recovery?

Mt. Taranaki eruption

Large eruption scenario

Days 1-5 – VAL 1 – unrest

Day 6 – VAL 2 – heightened unrest

Day 19 – VAL 3 – small eruption

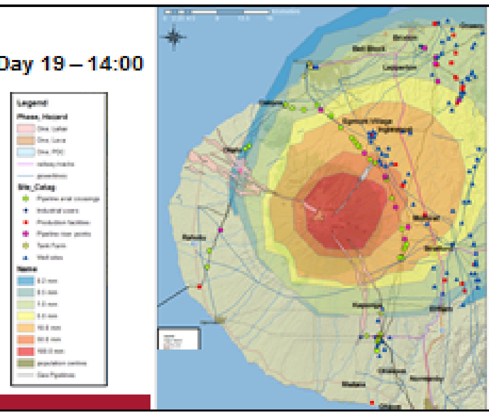
- 4km ash column – 0.05 km3 volume
- Lahars, PDCs & lava

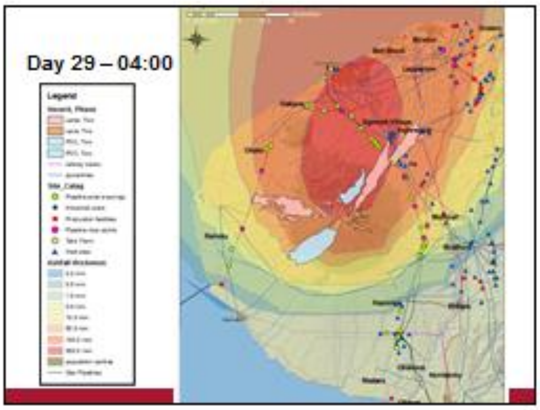
Day 29 – VAL 4 – large eruption

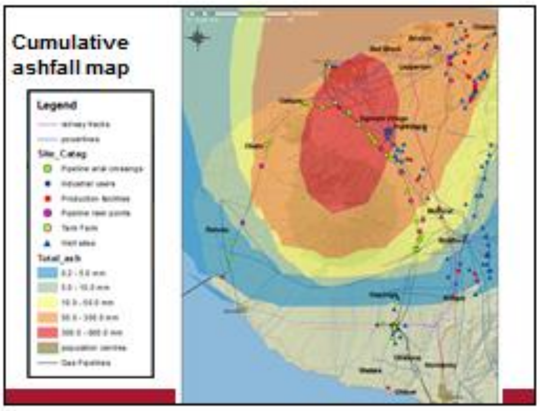
- 15 km ash column – 1 km3 volume
- Lahars, PDCs & lava

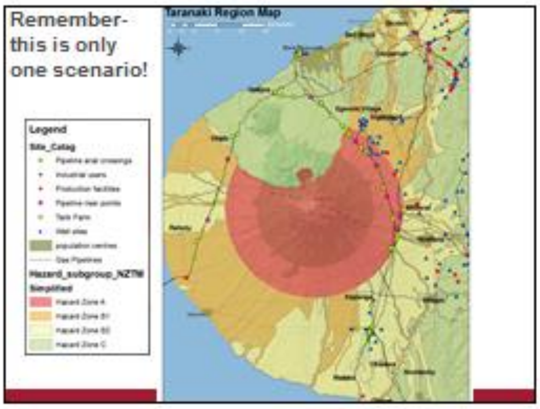
Cumulative ashfall and lahar map

Day 19 – 14:00









Discussion

What next?

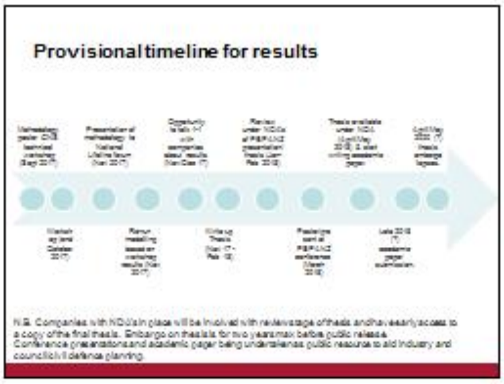
You guys

- Consolidate learnings from today
- Revisit your companies action plans for volcanic unrest
- Reconsider your dependencies
- Would site specific studies for high risk sites be advantageous?
- Run an exercise and include recovery
- Develop a collaborative sector forum to share ideas/plans and look at industry wide risk reduction/mitigation and response options. I.e. Policy/legislative/physical changes to assets
- Attend TCDEM lifeline group forums
- Keep talking to CD & MCDEM
- Are there conversations around expectation or other items to be had?
- Keep talking to GNS & Universities involved in volcanic hazards & impacts.

What next?

Zoe

- Collate results from today and report back to attendees
- Update categories/ vulnerability matrices
- Run impact models for an eruption scenario
- Write up thesis
- Sector briefing and one-one discussions as required
- Write academic paper
- Find a job……


Provisional timeline for results
N.B. Companies with NDA's in place will be involved with review stage of thesis and have early access to a copy of the final thesis. Embargo on thesis is for two years max before public release.
Conference presentations and academic paper being undertaken as public resource to aid industry and council/civil defence planning.


Questions?


TIME FOR
LUNCH
TIME FOR

A5.3 PARTICIPANTS

Name	Organisation
Craig Campbell-Smart	Taranaki Civil Defence
Gary Bedford	Taranaki Regional Council
Fred McLay	Taranaki Regional Council
Graham Alexander	Critical Contingency Operator
Nick Dawtry	WorkSafe New Zealand
Brad Scott	GNS Science
Tanya Hansen	Greymouth Petroleum Ltd.
Michael.Ellem	Shell Taranaki Ltd.
Melanie Sole	TAG Oil (NZ) Ltd.
Kate McCready	WestSide Corporation Pty Ltd
Stephen Dobson	Todd Energy Ltd.
Nicole Allen	University of Canterbury
Thomas Wilson	University of Canterbury
Alana Weir	University of Canterbury
Natalia Deligne	GNS Science
Al Den-McKay	First Gas Ltd.
Ricky Hann	Port Taranaki
Esther Tippett	Shell Taranaki Ltd.
Blair Odowda	Shell Taranaki Ltd.
George Hooper	WorleyParsons (Advisian)
Zoe Juniper	University of Canterbury
Paul Roberts	Lattice Energy
Julie Langford	CCO/Langford consulting
Dan Tan	Vector Ltd
Amy McSporran	University of Canterbury
Rod Briggs	Contact Energy Ltd
Katie Hogg	Taranaki Civil Defence

A5.4 FEEDBACK FOLLOW THE WORKSHOP

Comment fed back following the workshop included:

"Many thanks again for bringing us together for the workshop Friday. We got a lot out of it also."

"I enjoyed the workshop. Thought you did a great job at putting the information together and as well as impressed with the buy-in you achieved from the industry participants. Hopefully, it goes well – I will be pleased to contribute as I can, but the industry players will be able to offer up more specific comment."

"Just a short note to thank you for the invitation to the volcanic activity workshop last week. I thought that the session went well and everyone attending participated fully and got something out of it. In closing well done on your behalf, as I can imagine the amount of work that you have put in thus far on your thesis."

"Thank you for sharing this presentation. It is for sure that further study update would be great."

A5.5 OUTCOMES THE WORKSHOP

Below are the key findings from the workshop as presented to attendees in a follow-up report.

Petroleum Sector assets

Summary: The workshop had great discussions at the small and wider group level on how to group petroleum assets at a high level.

Key findings/conclusions:

- Consider physical asset functions and detach physical properties from the geographical location or operational dependencies for this study. Both other aspects can be considered in future studies
- Consider aerial crossings and pipelines to 0.7 m, as subsets of pipelines
- For this high-level study, group all storage tanks together irrespective of design or location
- Add buildings to a separate asset category.

Vulnerability Matrices

Summary: Some very robust detailed discussion that was cut short by time and lunch!

Key findings/conclusions:

- Buildings have been extensively covered by other research, and a matrix has not been developed here. Industrial users are out of scope
- Workshop suggestions led to me undertaking further literature review to understand asset design standards
- For slides 7-10, the shading on the left identifies the most and second most concerning hazards for each asset type

Dependencies

Summary: While the strawman put up considered each asset type separately, discussions converged on a single sector-wide appreciation.

Key findings/conclusions:

- The top four critical dependencies are what are critically required by the industry to continue to function in a 'business as usual' capacity.

- These assumptions come independently of any physical damage caused by volcanic hazards to the various assets.
- Additional constraints on the sectors ability to continue to function were discussed under the regulatory challenges, which was a cause for concern.

Regulatory challenges

Some of the key areas for further discussions:

- the impact of evacuation zones on the sector's ability to continue to function
- the need for an advanced warning to enable safe shutdown of assets within the evacuation zone
- the Government's expectation of the sector to continue to produce gas,
- what are the realistic recovery times and impacts for the country
- the lack of redundancy as a country for the gas supply
- the interplay of Health and Safety regulations on shutting down facilities pre-eruption and recovery
- lack of volcanic specific hazard assessments or considerations under some of the current legislation and regulatory processes
- the perceived inflexibility of some legislation and regulations in emergencies
- the interplay of industry regulations and legislation with the CDEM Act 2002